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Mapping suitable habitat for giant pangolin (*Smutsia gigantea*, Illiger 1815) in southern part of Campo Ma'an National Park, Southern Cameroon

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***Abstract*— *Giant pangolin is critically endangered, with declining populations due to rampant hunting and habitat loss. Considering that no information is provided on giant pangolin suitable habitats in Campo Ma'an National Park, this study aimed therefore at identifying suitable and preferred habitats for giant pangolin, determining the contribution of environmental variables to its habitat suitability and assessing the probability of giant pangolin occurrence to environmental variables in the southern part of CMNP. We conducted line transects and reconnaissance (recce) surveys for giant pangolin occurrence signs (N= 144). The occurrence data were combined with geophysical; soil, habitat, and anthropogenic variables using the Maximum Entropy (MaxEnt) species distribution model to map and predict the suitable habitat of pangolins. We found that 71 % of the area represents suitable habitats for giant pangolin while 29% represents unsuitable habitats. Both geophysical and soil variables played a vital role in determining suitable giant pangolin habitat, with aspect and soil organic carbon being key predictors. The probability of giant pangolin occurrence increased sharply in primary forests and dropped drastically in gallery, secondary and swamp forests. In contrast, the probability of finding giant pangolin indices decreased as Euclidian distance from the park interior to the nearest roads and villages increased. Conservation efforts should prioritise protecting and restoring primary forests with low soil pH, high silt content and low organic soil carbon as they provide essential habitats for giant pangolin. Furthermore, habitat destruction for roads and deforestation for the expansion of settlement should be mitigated.*

Keywords*— Human impact, habitat preference, habitat requirements, Maximum entropy modeling, giant pangolin.

I. INTRODUCTION

Pangolins (Mammalia: Pholidota) comprise eight insectivorous species with four native to Asia, and include the Chinese pangolin (*Manis pentadactyla*), Indian pangolin (*Manis crassicaudata*), Malayan pangolin (*Manis javanica*) and Philippine pangolin (*Manis culionensis*) (Gaubert and Antunes, 2005). The Philippine, Malayan and Chinese pangolins are all classified as "Critically Endangered" (Challender et al., 2019; Schoppe et al., 2019). Four species are found in Africa and include: Temminck's pangolin (*Smutsia temminckii*), giant pangolin (*Smutsia gigantea*), black-bellied pangolin (*Phataginus tetradactyla*) and white-bellied pangolin (*Phataginus tricuspis*). White-bellied and giant pangolins are classified as "Endangered" (Nixon et al., 2019; Pietersen et al., 2019a), while black-bellied and Temminck's pangolins are classified as "Vulnerable" (Ingram et al., 2019; Pietersen et al., 2019b). The Cameroon national wildlife law classifies giant, black- and white-bellied pangolin species under Class A, which prohibits the hunting, capture, killing and trade of pangolins and their derivatives in the country (MINFOF, 2020). All eight pangolin species are listed in Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), with a zero annual export quota for wild-caught individuals traded primarily for commercial purposes (CITES, 2017).

African pangolin populations are rapidly declining due to hunting (Challender and Hywood, 2012), habitat degradation and loss (Challender et al., 2016; WABiCC, 2020), and illegal trade of their scales from Africa to Asia, with a particular focus on Central Africa (Challender et al., 2020; Ingram et al., 2019). Pangolins have been extirpated in some of their suitable habitats (Aisher, 2016; WABiCC, 2020), hence becoming a focal point of interest to conservationists (Kaimo et al., 2019; Angwafo et al., 2019). Conservation of wild pangolins has been challenged by the difficulty in locating them, especially as the depth of their burrows often reach several meters (Karawita et al., 2018). Locating wildlife helps in mitigating conflicts between humans and animals, which is essential for both human safety and wildlife conservation (Treves and Karanth, 2003). Another challenge is the fact that other wildlife species share habitat types and prey preferences with pangolins. For example, aardvark and giant pangolin prey on ants and termites and both dig resting burrows with aardvark mostly using their burrows for a relatively short period of time after which time they are occupied by giant pangolin (Hoffmann et al., 2020, Kingdon, 2015).

Species distribution models (SDMs), also called Ecological Niche Models or Climate Envelope Models, are quantitative methods that combine data on the known occurrence of a species with predictor variables, statistical models, and computer algorithms to i) compute values for each predictor and the way it affects the species of interest at each site of known occurrence, and then ii) identifies suitable areas based on these predictor variables (Carpenter et al., 1993; Duan et al., 2014, Elith and Leathwick, 2009; Fielding and Bell, 1997; Wisz et al., 2008). These models are a fast gaining grounds in the field of research (Brotons, 2014), where they are frequently utilised to support decision-making in various fields such as ecology, biogeography, biodiversity conservation and natural resource management (Franklin, 2010; Franklin, 2013; Guisan and Thuiller, 2005; Guisan et al., 2013; Newbold, 2010). The SDMs now assist in directing field surveys (Peterman et al., 2013), assessing the effects of climate change on species, and improving conservation planning (Fitzgerald et al., 2018; GuilleraArroita et al., 2015; Zellmer et al., 2019).

The maximum entropy-MaxEnt (e.g. version 3.4.4) is used to predict habitat suitability for giant pangolin (Phillips et al., 2006). This approach relies on the occurrence points and comparisons between predictor variable values at presence localities and those at randomly selected background sites (Phillips et al., 2006). MaxEnt creates and randomly selects false absence points (background data) by considering the species to have the same likelihood of occurrence across the study area (Lahoz - Monfort et al., 2014; Merow et al., 2013; Phillips and Dudík, 2008), with some few limitations such as the occurrence sampling bias and the use of false absence points instead of true absence points (Elith et al., 2011; Kramer-Schadt et al., 2013; Phillips and Dudík, 2008; Radosavljevic and Anderson, 2014). It is however still useful using a few occurrence points to yield good results and to prevent model over-fitting (Mohammadi et al., 2019; Phillips and Dudík, 2008; Spiers et al., 2018).

In sub-Saharan Africa, pangolins mostly inhabit primary and secondary forests, forest-savannah mosaics, swamps, gallery forests, wooded savannah and wet grasslands (Kingdon, 2015; Nixon et al., 2019; Hoffmann et al., 2020; Mouafo et al., 2023), as well as areas near water sources with minimal human activities (Hoffmann et al., 2020, Nixon et al., 2019). Several studies have reported on the effects of environmental factors and human activities on habitat suitability of pangolins (Table 1).

Table 1: Relationship between environmental variables of suitable pangolin habitats and their occurrence in some study sites across the world

Predictor variable	Pangolin occurrence	Country	Study site	References
Aspect	Positive	China	SNNP	Bhandari and Chalise (2014)
Aspect	Positive	China	PMGDN	Dhakal (2016)
Slope	Negative	China	DNR	Wu et al. (2003)
Slope/distance to road and villages	Negative	India	LFLSWSL	Karawita et al. (2018)
Slope/distance to road and villages	Positive	China	PNPAN	Sharma et al. (2020)
Soil pH/coarse fragment concentration	Positive	Cameroon	PFSTACC	Mouafo et al. (2023)
Soil pH	Positive	China	LP	Shrestha et al. (2021)
Soil pH	Positive	China	CFDDN	Rai et al. (2019)
Forest density	Positive	China	LPAN	Suwal et al. (2020)
Distance to road	Negative	China	DIAUN	Katuwal et al. (2017)
Soil organic carbon/soil bulk density	Negative	China	SG	Zhang et al. (2021)
Elevation/NDVI	Positive	Cameroon	PFSTACC	Mouafo et al. (2023)
Elevation	Positive	India	PP	Waseem et al. (2020)

SNNP Shivapuri Nagarjun National Park, *PMGDN* Palungta Municipality of Grkha District, Nepal, *DNR* Dawuling Natural Reserve, *LFLSWSL* Lowland Forested Landscape of southwest Sri Lanka, *PNPAN* Protected and non-protected areas of Nepal, *PFSTACC* Protected forest-savannah transition area of central Cameroon, *LN* Lowlands of Nepal, *CFDDN* Community Forest of Dolakha District of Nepal, *LPAN* Lowland plain areas of Nepal, *DIAUN* Dhankuta and Ilam administrative Unit of Nepal, *SG* Songnen grassland, *PP* Potohar plateau.

However, little is known of how certain environmental variables such as clay and silk content of the soil, bulk density of the soil, aspect (burrow orientation), and slope may affect the distribution of pangolins and giant pangolin in particular. In Cameroon, several studies have focused on confirming the occurrence of the giant, black- and white-bellied pangolins (Angwafo et al., 2019; Mouafo et al., 2021, 2022; Difouo et al., 2021; Ichu, 2019; Ichu et al., 2017; Harvey-Carroll et al., 2022; Fopa et al., 2020), and documenting local ecological knowledge of pangolins (Kaimo et al., 2019, 2025; Mouafo et al., 2021), trade on pangolins (Mouafo et al., 2022; Ingram et al., 2018, 2019; Harvey-Caroll et al., 2022) and relative abundance of pangolins (Bruce et al., 2018; Ichu et al., 2017; Amin et al., 2023; Angwafo *et al.*, 2019). Recently, only a few studies have been conducted on the suitable habitats of pangolins in Cameroon. For example, Mouafo et al. (2023) reported that Euclidean distance to the national park's boundaries, Normalised Difference Vegetation Index (NDVI), elevation, and distance to rivers were significant predictors of the giant pangolin suitable habitats at Mbam et Djerem National Park in Cameroon. According to Mouafo et al. (2023), most of the park (79.76%) was unsuitable for giant pangolin while suitable habitats (20.24 %) were dispersed across densely forested areas, ecotones, and savannas.

Giant pangolin is highly valued for its meat and scales, leading to intense hunting pressure (Hoffmann et al., 2020). The expansion of agriculture, urbanization, and logging have led to the destruction and fragmentation of its habitats, making it difficult for it to find food, shelter and mates (Fopa et al., 2020). As habitats are destroyed, pangolins and giant pangolin in particular are forced into agricultural areas and plantations, leading to conflicts with farmers who view them as pests. Climate change alters the availability of food resources, making it harder for giant pangolin to survive (Mbow et al., 2017). There is still insufficient data on the ecology and ethnozoology of giant pangolin with a great gap in their scientific related knowledge (Ingram *et al.*, 2019; Pietersen and Challender, 2020). This knowledge gap is greatly attributed to the cryptic and elusive behavior of local pangolin species thereby constraining biomonitoring efforts (Willcox *et al.*, 2019; Hoffmann *et al.*, 2020). This has greatly contributed to ineffective conservation actions. The construction of roads, dams, and other infrastructure projects are fast leading to giant pangolin habitat destruction and fragmentation (Fopa et al., 2020). The demand for meat and scales in Asia drives the poaching and trade of giant pangolin in Cameroon (Ingram et al., 2018).

In the southern section of Campo Ma'an National Park (CMNP), the abundance and distribution of pangolins and giant pangolin in particular has been reported (Kaimo et al., 2024; Kaimo et al., 2025), but the habitat preferences of giant pangolin in this area has not been known. Previous studies on pangolin trade have focused solely on trade dynamics without providing insights into habitat suitability (Ichu, 2019). For example, Ichu (2019) reported that illegal pangolin meat and scales coming from the southern region of Cameroon are mostly poached from CMNP and transported to markets in Kribi and Ebolowa, for consumption while the scales are usually transported to Yaoundé and Douala for sale. Given the limited prioritization of pangolin research in the park in the past, it is important to initiate long-term studies to better understand distribution and habitat requirements, which is essential for formulating effective conservation strategies and monitoring population trends in the future. This study therefore sought to better understand the habitat needs of giant pangolin in southern CMNP with the following research questions: (i) what are the environmental variables that influence giant pangolin distribution, and how do they affect its distribution? (ii) what is the proportion suitable giant pangolin habitat and how is it distributed within the study area? Based on these research questions, we hypothesized that: (i) the distribution of giant pangolin in southern CMNP would be affected by Euclidian distance to human settlements and roads (Hoffmann et al., 2020), and soil types (Mouafo et al., 2023) considering that giant pangolin is a burrowing species and (ii) that suitable habitat for giant pangolin is sparsely distributed in the study area with giant pangolin preferring primary forests to other forest types. Based on these questions, this study aimed to 1) map suitable giant pangolin habitat, 2) find out the contribution of environmental variables on giant pangolin habitat suitability, and 3) determine the probability of giant pangolin occurrence with respect to environmental variables in the park using Maximum Entropy (MaxEnt) species distribution model.

II. METHODS

Study area

Campo Ma'an National Park (2°15' – 2°30' N, 10°00' – 10°15'E; Fig. 1) was created in 2000 merging Campo Wildlife Reserve, 1,582 km², and the adjacent Ma'an forest plantation, 990 km² (Owono, 2001). Average annual rainfall in CMNP ranges from 2800 mm, near the Atlantic coast to 1670 mm, further inland (PNCM, 2014; Tchouto et al., 2006). The mean annual temperature is about 25°C, although some variation occurs between the western and eastern sections of Campo Ma'an. Campo Ma'an and its environs belong to the Atlantic basin drainage system. Two main watersheds are found in the environs of Campo Ma'an: The Ntem and the Lobé watersheds, characterized by rivers which flow in a North-east and South-west directions (Mbenoun, 2017). The climate of CMNP and its peripheral zone is of the four-season coastal unequal type, including 2 dry seasons and 2 rainy seasons, namely: a long dry season from late November to February, a short rainy season from March to May, a short dry season from from June to mid-August and a long rainy season from mid-august to November (Mbenoun et al., 2017). Hydromorphic and ferralitic soils are the dominant soil types with hydromorphic soils found in the valleys and lowlands; while ferralitic soils develop from acidic parent rocks (Tchouto *et al.*, 2006).

The forest is evergreen and has a predominantly closed canopy, and is described as Atlantic Biafran forest with many plant species in the Caesalpiniaceae family (Mbenoun et al., 2018; Tchouto el al., 2009). The forest region containing the Campo Ma'an National Park is believed to have persisted as a tropical rainforest throughout the Pleistocene era, based on the distribution of slowly dispersing plants species and high degrees of endemism (Tchouto et al., 2009). The central part of the study site (Depicar Island; Fig. 1) consists mainly of primary and secondary forests. The primary forest consists of a late serial climax community forest that has never been logged and has developed through natural processes. It is a mixture of both swampy and gallery forests. The secondary forest mostly consists of colonization trees that regenerated after the primary forest has been harvested. Extending far beyond the park boundaries are the Equatorial Guinea to the south, Atlantic Ocean to the West, Vallee-du-Ntem and Mvila to the east. The park is home to more than 80 species of mammals including more than 350 forest elephants (*Loxodonta Africana cyclotis*), duikers, hippos, bush pigs, pangolins, black colobus, mandrills (*mandrillus sphinx*) and leopards (*Panthera pardus*) (Dongmo *et al*., 2015; Mveng, 1984). A small population of forest buffalo resides in the southern area of the park (Bekhus *et al*., 2008). It harbours population of more 700 critically endangered western lowland gorillas (*Gorilla gorilla*) and 700 endangered central chimpanzee (Mattheus and Mattheus, 2004).

The national park is surrounded by five forest logging concessions, industrial rubber plantations, industrial oil palm plantation and a buffer zone (Tchouto et al., 2006). Selective logging took place in 1994–1995, leaving logging roads through the park (Bekhuis et al., 2008). The park is subject to many threats, mainly due to logging, poaching, agricultural activities and coastal development (WWF Global, 2018). Construction of the Memve'ele hydroelectric dam and the Kribi deep-sea port represent additional threats to the biodiversity of the region (Fiona et al., 2015). Due to the high biodiversity and need for continued and sustainable conservation, Campo Ma'an has been proposed as a pilot ecotourism site (Forje et al., 2021).

Our study area (799.46 km^2; Fig. 1) is located in the southern section of the CMNP.

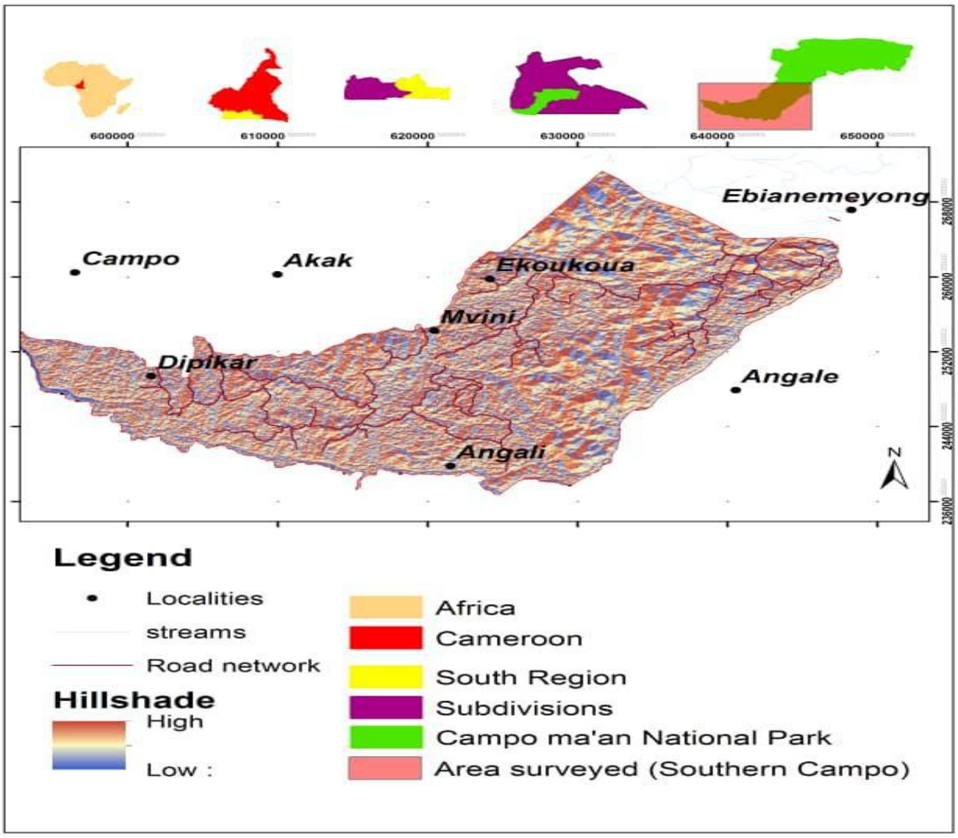

Fig.1. Study area in Campo Ma'an National Park showing human settlements and road network.

It is surrounded to the west and east by forest logging concessions including, Forest Management Unit (FMU) 09-025 to the west and FMU 09-024 to the east. There are also mining companies bordering this area including, COMP MINIERE CMR MINKO to the south, SINOSTEEL CAM SA LOBE to the west and COMP MINIERE CMR BINKO to the north east. The Campo compartment is located to the west where the few villages in close proximity include Mvini, Nko'elon, Akak, Nazareth whereas to the east is the Ma'an section characterized by Ebialmeyong, Ekoukoua, Abang and Oveng as those villages in close proximity with the study site.

Survey design and occurrence data

Prior to fieldwork, a meeting was held with park authorities to design a plan for a recce survey (Mouafo et al., 2023). We conducted four 2-km recce surveys to identify core areas of giant pangolin activity, focusing on giant pangolin presence signs, including sleeping burrows locations, feeding signs, food prints, and faecal matter (Kühl, 2008). Based on the recce surveys, we produced 20 geospatial line transects each 2 km in length in ArcGis10.2. 2 and overlaid them on a map of the study area following a random design (Buckland et al., 2001). The choice of 20 transects were based on the accessibility of major habitat types in the study area.

The line transects were oriented to cut across several habitat types (primary, secondary, gallery and swampy forests), and interconnected with each other by a 4 km recce-transect. In the field, the first author, two experienced forest guides and two park eco-guards surveyed recce-transects monthly from April to August 2022 (rainy season) and from October to December 2023 (dry season) for signs of giant pangolin activity (giant pangolin presence data). We recorded the presence locations of giant pangolin using the Global Positioning System device (Garmin etreX 10) following Mahmood et al. (2015). Additionally, we attached five Bushnell Core T87 camera traps on trees between 30-50cm above ground level along 5 transects targeting five active burrows of pangolins to increase the probability of detecting them. We programmed cameras to operate to take three photographs and then continue taking a video for one minute video. After installing a camera trap in the field, the performance of the camera was checked using the "Walk Test" option to confirm that the camera sensor was functioning normally. During transect monthly visits we inspected camera traps to replace SD cards and batteries as needed (Fotang et al., 2023).

Because of their elusive nature, pangolins in general are difficult to observe directly, as such, indirect evidence is often used to identify their presence (Mahmood *et al.*, 2014; Perera & Karawita, 2020). Also, to solve the problem of accurate identification of indirect signs of giant which is sometimes problematic due to their similarity with those of *Orycteropus afer* (aardvark), both local knowledge and verifiable evidence were used following previous studies on pangolins (Newton *et al.*, 2008; Karawita *et al.*, 2018; Nash *et al.*, 2020).

In total, we documented 144 giant pangolin occurrence indices, which consisted of resting burrow locations (39), feeding burrows (90), food prints (10), and faecal matter (5), across a survey effort covering 320 km for the two survey periods. Among the resting burrows were 20 active, 19 inactive ones and among the feeding burrows were 63 fresh and 27 old feeding ones giving a total of 129 burrows.

Based on the total number of giant pangolin occurrence indices, the Habitat Preference Indices (HPIs) for each habitat type were calculated. The highest HPI was recorded in primary forest for both the rainy and dry seasons. Table 2 shows the HPI recorded in different habitat types in the study area.

Table 2: Habitat preference indices of giant pangolin recorded in different habitat types over seasons of the year

Seasons	Habitat types	Area (km²)	Proportion (%)	Total number of indices	HPI	Rank per season
Rainy	Primary forest	516.47	66.69	74	1.11	1
Rainy	Secondary forest	103.4	13.35	6	0.45	3
Rainy	Gallery forest	96.56	12.48	10	0.80	2
Rainy	Swamp forest	57.99	7.48	0	0	4
Dry	Primary forest	516.47	66.69	46	0.69	1
Dry	Secondary forest	103.4	13.35	3	0.22	3
Dry	Gallery forest	96.56	12.48	4	0.32	2
Dry	Swamp forest	57.99	7.48	0	0	4

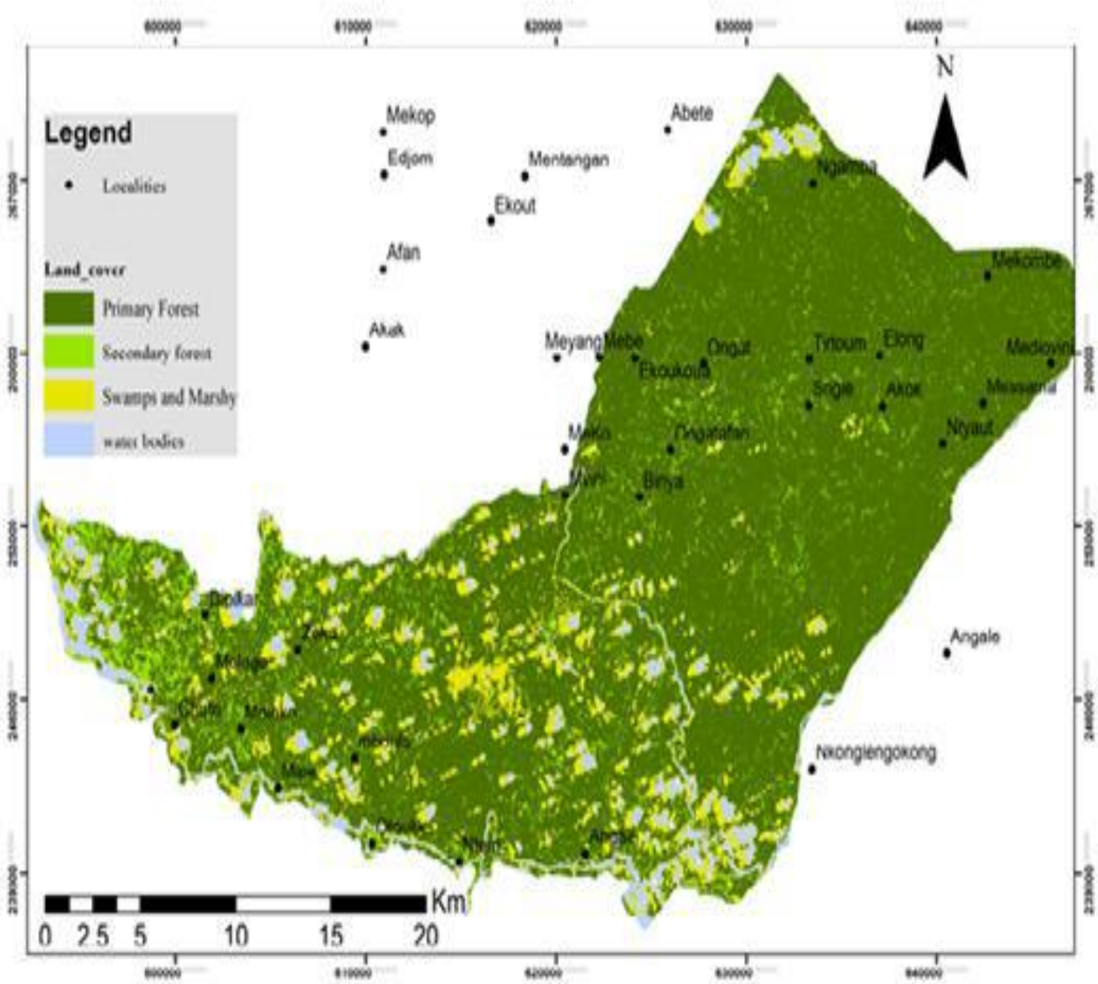

Fig.2. Land covers predictor for modeling

Spatial thinning was performed using the thin function within the spThin R package to remove duplicate points (Aiello-Lammens et al., 2015). This process reduced the giant pangolin occurrence points to 173, which were utilized in the final model.

Environmental variables

To model the habitat suitability of giant pangolin within the study area, we first obtained land cover data (primary forest, secondary forest, swamp forest and water bodies) for the study area from a land cover classification map (Fotang et al., 2023; Fig. 5) using Landsat 8 image bands (Debela et al., 2021). Second, we obtain geophysical variables by calculating aspect, slope, hill shade and land curvature in ArcGIS10.2.2 using elevation data from a Shuttle Radar Topography Mission 30 m resolution Digital Elevation Model (Jarvis, 2008). Third, we re-scaled the raster layers of all environmental variables at 30 x 30 m grid cells or pixels (Fotang et al., 2023; Mouafo et al., 2023). Forth, we converted the raster layers to points (number of pixels) and used the Kernel Density interpolation method in ArcGIS10.2.2 to calculate the densities of primary forest, secondary forest and swampy/marshy areas and water bodies per km² (Fig. 2; Tarjuelo et al. 2017).

Finally, we used Google Earth images to digitalize roads and villages and then measured the distance to each feature as Euclidian distance (Fotang et al., 2023). We then calculated the distance of pangolin presence points to the digitalized roads and villages using the Euclidian distance function in ArcMap 10.3 (Fig. 6).

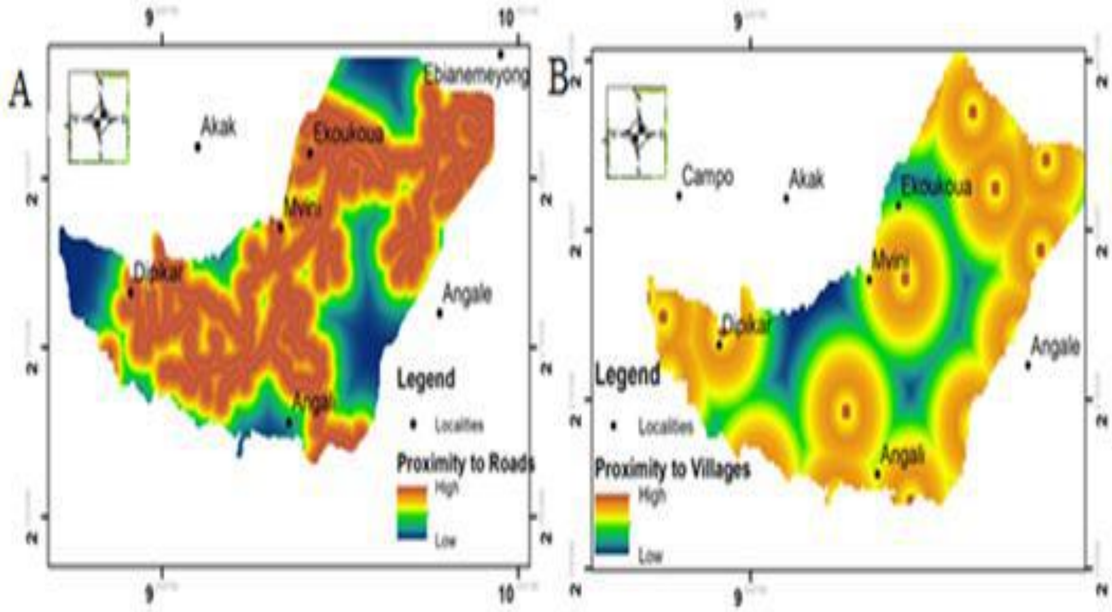

Fig.3. Anthropogenic predictors included: Distance to nearest road (A), distance to villages (B).

We obtained soil variables from the SoilGrids 250m database (https://www.soilgrids.org; Hengl et al., 2017). Seven soil variables were used to provide predicted values for the surface soil layer (0–30 cm depth) among which were four soil texture variables (clay content, coarse fragment, sand, silt) and three chemical variables (bulk density, water pH and soil organic carbon). These particular soil variables were chosen because there is still insufficient data concerning their effects on habitat suitability of the giant pangolin in Africa unlike in Asia. We checked for collinearity among land cover, geophysical, soil and anthropogenic predictors of pangolin occurrence separately using the *Uncertainty Analysis for Species Distribution model* (USDM) package in R (Naimi et al. 2014). We set a correlation threshold of 0.7 and used the variance inflation factor (VIF) to choose which variable to remove (Fox, 2015). We found no significant collinearity among pairs of land cover, geophysical, soil and anthropogenic predictors. Finally, we ran four separate MaxEnt models for each of the of environmental predictors (Figs. 4I and II)

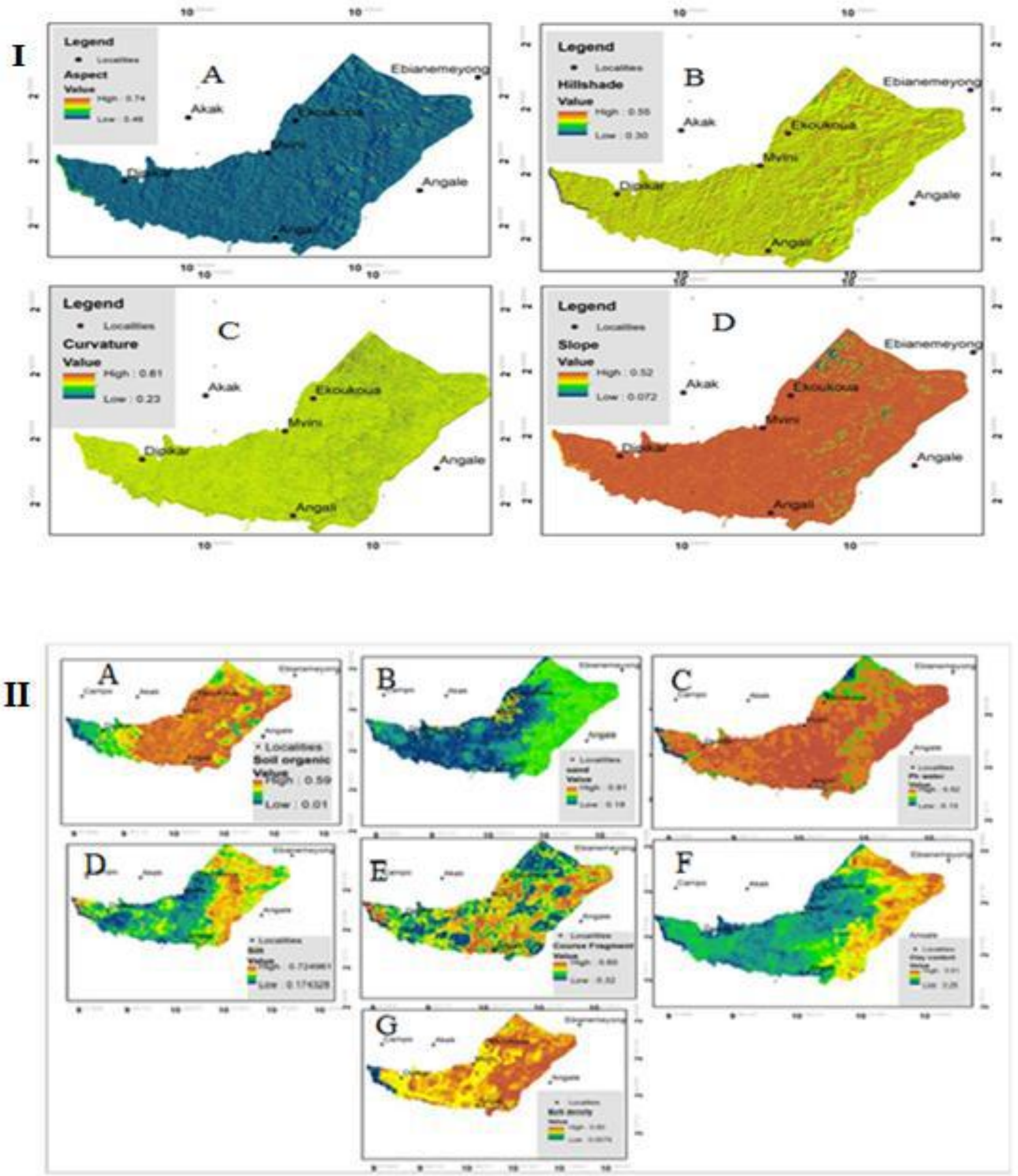

Fig.4. I) Geophysical predictors: aspect (A), hillshade (B), land curvature (C) and Slope (D); II) Soil predictors: soil organic value (A), sand, (B) water pH (C), silt (D), coarse fragments (E), clay (F) and bulk density (G).

Species distribution model

To model habitat suitability and preference for giant pangolin, we used 144 giant pangolin presence signs recorded during our survey. Among these, 104 points were used to train the model, while 40 points were reserved to test its performance. Subsequently, we integrated 10,110 additional data points pertaining to geophysical variables, thereby yielding a cumulative dataset of 10,214 points for the geophysical model. Regarding soil variables, our analysis focused on 121 giant pangolin presence locations. Of these, 91 points were utilised for training and 30 for testing purposes.

Since MaxEnt modeling is a machine learning process which simulates a known real model with potential complexity based on a certain algorithm, its accuracy cannot be determined with precision, thus requiring preventative measures to be taken to reduce model over-fitting (Yan et al., 2021). We therefore prevented over-fitting by selecting parameters used to set the program. An optimal model was selected by setting the appropriate regularization multiplier (RM) and the corresponding feature combination (FC) (Phillips et al., 2006, Yan et al., 2021). MaxEnt normally provides five feature modes (Linear (L), quadratic (Q), product (P), hinge (H), and threshold (T)) which can be used alone or in combination depending on the sample size (Elith et al., 2011). The L feature is always running, the Q feature starts to run with at least 10 occurrences, the H function requires a minimum of 15 occurrences, and the P and T features require >80 samples (Elith et al., 2011, Yan et al., 2021). We initially used the default settings of MaxEnt, but set the output format to logistic, the maximum number of iterations to 1,000, LQHP feature types (since our sample size was greater than 80), and a 20-fold random cross-validation to estimate errors around fitted functions. For the RM, we used a step-by-step approach by successively running models with different RM values (0.5, 1.0, 1.5, 2.0, 2.5 and 3.0) to constrain MaxEnt, and prevent over-fitting of the models (Phillips et al., 2008, Breiner et al., 2015).

We evaluated the model's performance by analyzing the area under the curve (AUC) of the receiver operating characteristic (ROC) curve. The AUC is generally between 0 and 1. We considered AUC values greater than 0.9 as excellent, 0.8–0.9 as very good, 0.7–0.8 as good, 0.6–0.7 as fair and ≤ 0.6 as poor (Araújo et al., 2005; Duan et al., 2014; Mouafo et al., 2023). We then assessed the individual contribution of environmental predictors using the jackknife test (Pearson et al., 2007; Thorn et al., 2009). The predicted habitat suitability were grouped into four classes based on how close the local environment is to the species' optimal conditions, with higher values standing for the most suitable areas (Hirzel et al., 2006): 0.0–0.25 (highly unsuitable habitat), 0.25–0.5 (unsuitable habitat), 0.50–0.75 (suitable habitat), 0.75–1 (highly suitable habitat) (Campos et al., 2015; Morris et al., 2016).

III. RESULTS

Suitable habitat area and habitat preference

The MaxEnt model fit was good for soil variables with an AUC of 0.705 (SD±0.049), very good for anthropogenic variables with an AUC of 0.955, fair for geophysical variables with an AUC of 0.615 (SD±0.043) and fair for habitat variables with an AUC of 0.664. We found that 39.5% of the study area was highly suitable for giant pangolin, 31.5% was moderately suitable, 16.5% unsuitable and 12.5% highly unsuitable for (Fig. 5).

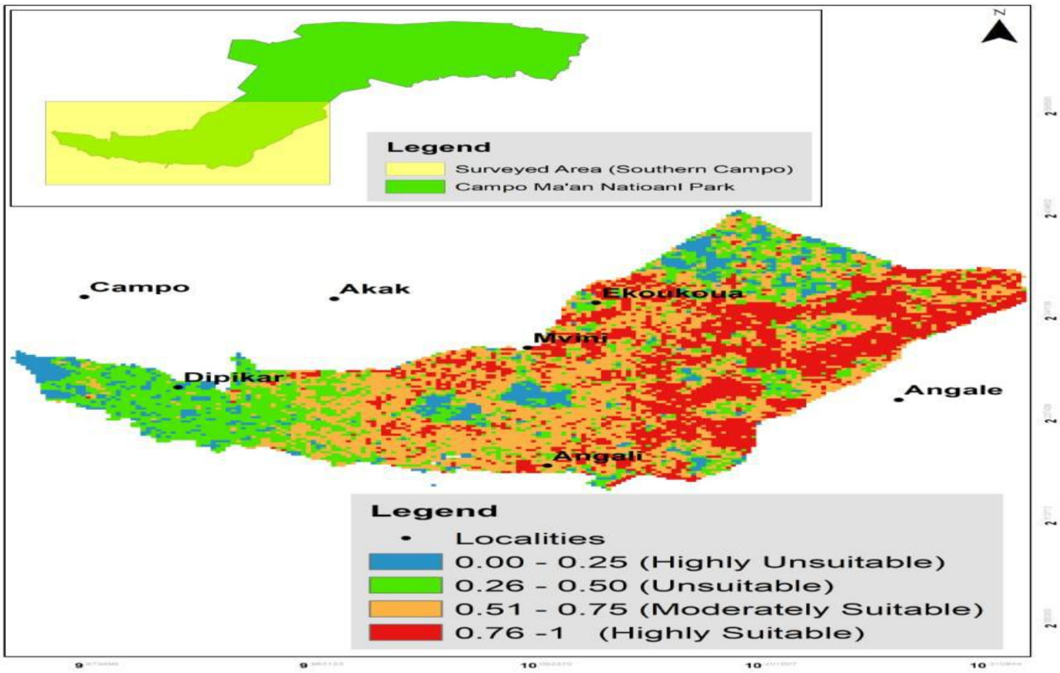

Fig.5. Predicted habitat suitability map in the southern compartment of Campo Ma'an National Park.

Additionally, giant pangolin occurrence signs were preferentially found in the primary forest (76.6%, n=144), followed swampy forest (12.1%, n=22), gallery forest (5.0%, n=9) and secondary forest (3.3%, n=6). Our data suggest that giant pangolin tends to prefer primary forests, with a smaller proportion of occurrence signs found in other forest types such as swampy, gallery, and secondary forests

Percent contribution of environmental variables to the MaxEnt model

Aspect was the most important geophysical predictor of giant pangolin habitat suitability, contributing 49.1% to the model's predictive accuracy. This was followed by slope, which accounted for 22.2% of the model's accuracy, then hillshade at 17%, and land curvature with the least impact at 11.4% (Table 3).

Table 3. Geophysical and soil variables and their contributions to pangolin habitat suitability

Category of environmental factor	Variable description (Unit)	Variable contribution (%)
Geophysical variables	Aspect (degrees)	49.1
	Slope (degrees)	22.2
	Hills shade	17.3
	Curvature	11.4
Soil variables	Soil organic carbon stock (g/kg)	30.3
	Silk content in a kilogram of soil (g/kg)	19.9
	Concentration of coarse fragment in the soil (cm^3/dm^3)	16.5
	Sand content in a kilogram of soil (g/kg)	16.3
	Bulk density (g/cm^3) or kg/m^3	14.1
	Clay content in a kilogram of soil (g/kg)	2.1
	pH index measured in water solution	0.8

Among geophysical variables, evaluating the variables individually, jackknife test corroborated that aspect was the most significant contributor to model fitness (Fig. 6-I). Among soil variables, soil organic carbon contributed the most at 30.3%, whereas the pH index in water solution had the least impact at 0.8%. If variables are considered alone, the jackknife test also supported soil organic carbon stock as the most significant contributor to model fitness among soil variables (Fig. 6-II).

Probability of pangolin occurrence with environmental variable

Geophysical variables

The probability of encountering giant pangolin burrows decreased from the northern (0-22.5^o), north eastern (22.5-67.5^o), and eastern (67.5-112.5^o) regions of the study area unlike in the south eastern (112.5-157.5^o), southern (157.5-202.5^o) and western (≥247.5^o) areas where the probability was higher (Fig. 7A). The probability of finding giant pangolin burrows decreased when steepness increased from 20-60^o in a given surface area, thus suggesting that giant pangolins preferred gently sloping environments (5-20^o; Fig. 7B). The Azimuth angle of light source of between 0-180^o was highly suitable for pangolin occurrence. The sun's inclination of 180^o to the surface's altitude produces a negative effect to giant pangolin habitat suitability (Fig. 7C). In figure 7D where the positive variable values indicate more curved or relatively contoured areas, and vice versa for the negative variable values, the behaviour of the curve stipulates a higher likelihood of giant pangolin occurring in more contoured environments than in more straightened surfaces.

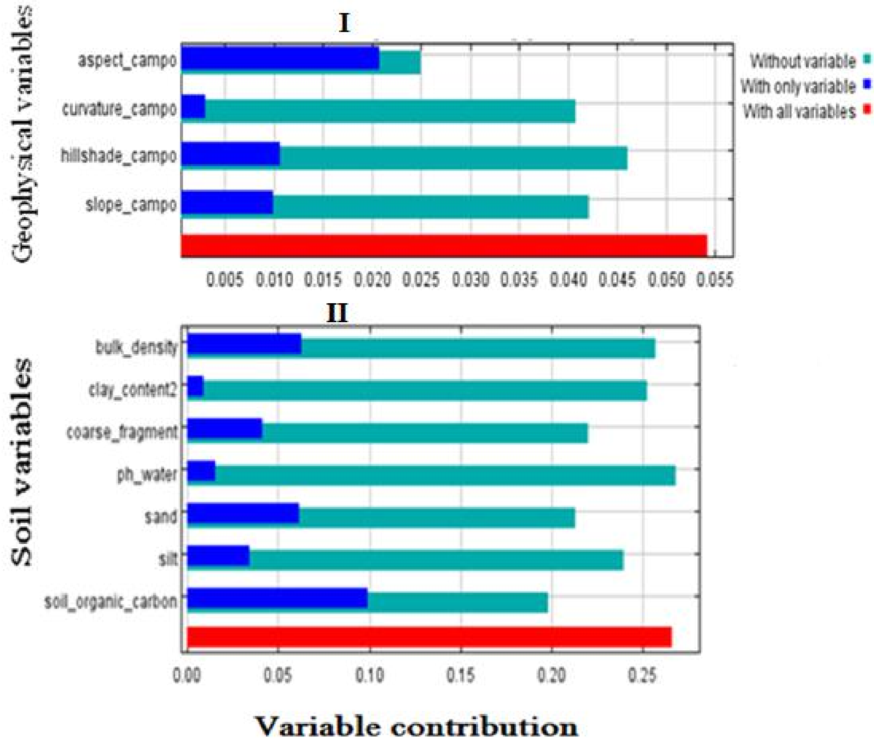

Fig.6. Jackknife regularized training gain and contribution of I) geophysical variables; and II) soil variables to the fitted model. Blue bars show the model gain when variables are considered alone. Dark-green bars show the training gain without variable while red bars show the training gain when all variables are used in the model.

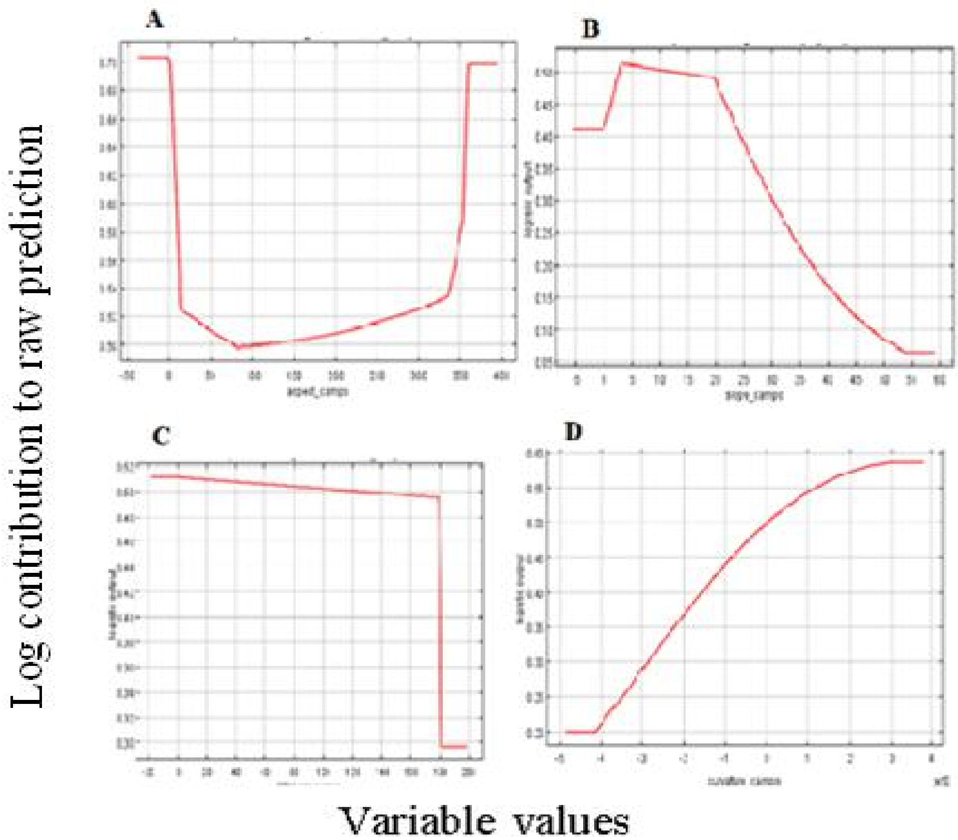

Fig.7. Response curves showing the effects of A) aspect of burrows B) Slope of land surface, C) Hill shade, and D) Land curvature on the predicted habitat suitability for giant pangolin Smutsia gigantea

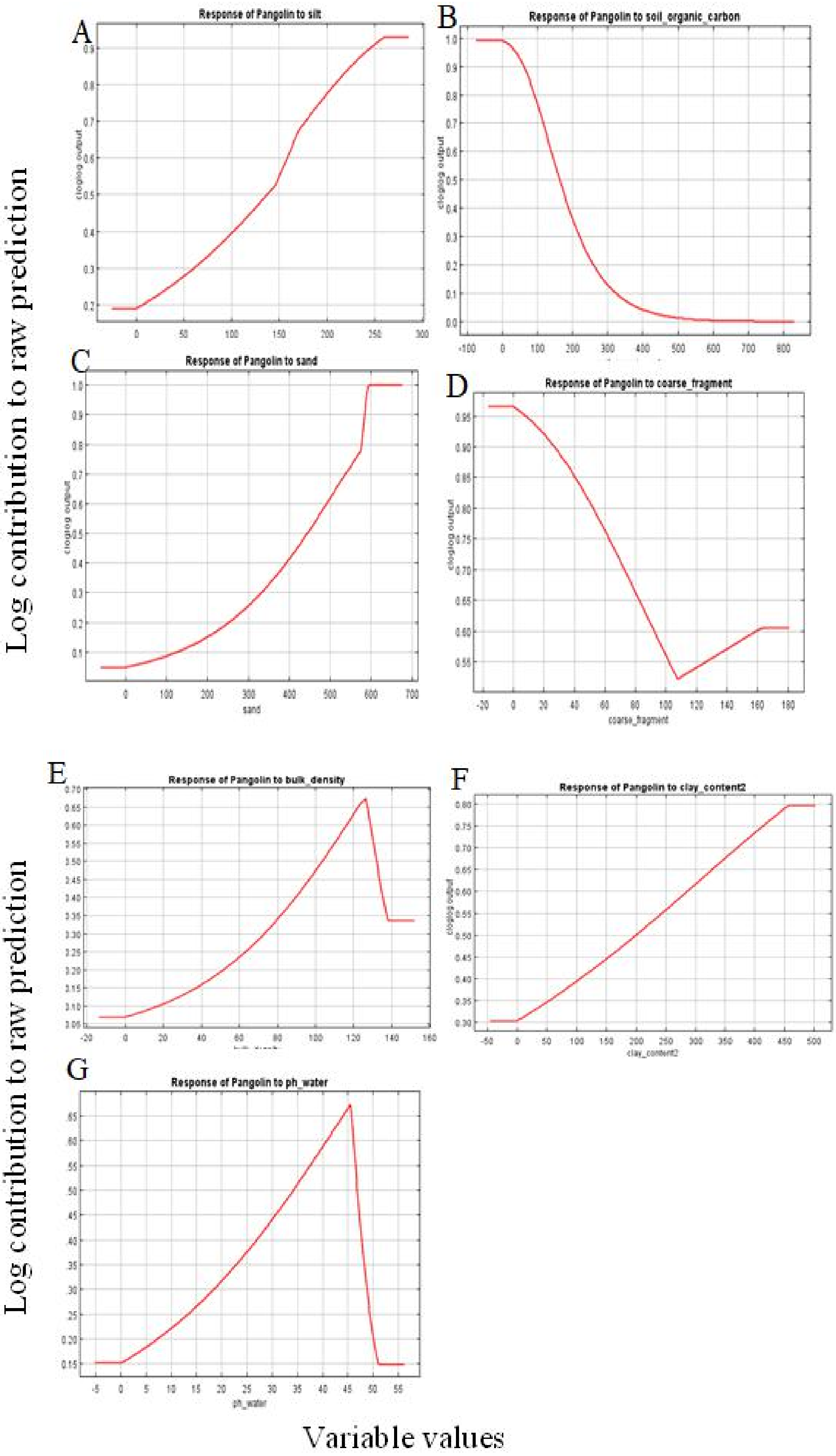

Fig.8. *Response curves showing the effects of A) Silt content in a kilogram of soil, B) Soil organic carbon stock in a kilogram of soil, C) Sand content in a kilogram of soil, D) Concentration of coarse fragments in the soil, E) Bulk density in cubic metre per kg of soil, F) Clay content in a kilogram of the soil and (G) pH of water on predicted habitat suitability for giant pangolin (Smutsia gigantea) in the southern section of Campo Ma'an National Park.*

Soil variables

The probability of giant pangolin occurrence increased with silt, sand, and clay contents, and also with soil bulk density (Fig. 8). Soils with bulk densities superior to 125 kg/m^3 showed low probability of giant pangolin occurrence (Fig. 8E). In contrast, giant pangolin occurrence decreased with increase in soil organic carbon stock and concentration of coarse fragments in the soil (Fig. 8). For coarse fragments, soils with concentrations between 110 and 180 cm^3/dm^3 with peak at approximately 162cm/dm^3 showed the highest probability of pangolin occurrence (Fig. 8D). The probability of giant pangolin occurrence increased as water pH (value multiplied by 10) increased from 0 to 4.6 (Fig. 8G), indicating that giant pangolin thrives better in acidic soils.

Habitat and anthropogenic variables

The probability of giant pangolin occurrence signs increased sharply in primary forests, peaked in the transition zone between primary and gallery forest (Fig. 9). In contrast, giant pangolin occurrence dropped drastically in secondary forests to almost zero in swamp forest.

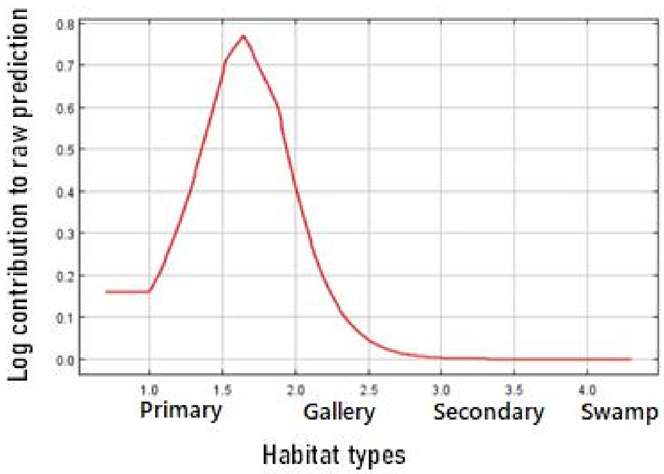

Fig.9. Response curve showing the effect of land cover on predicted habitat suitability for giant pangolin

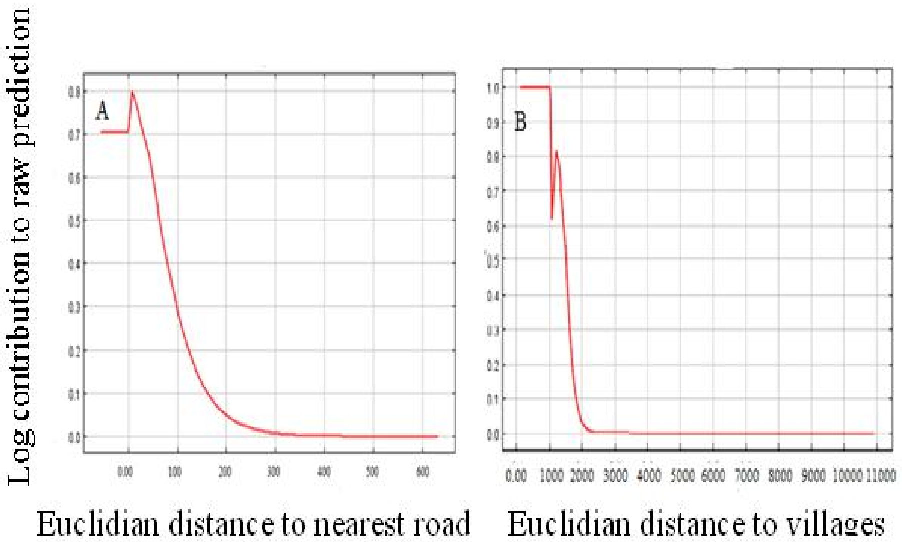

Fig.10. Response curves showing the effects of (A) Euclidian distance to nearest road and (B) Euclidian distance to villages on predicted habitat suitability for giant pangolin (Smutsia gigantea)

The probability of finding a giant pangolin decreased as the Euclidean distance from the park interior to the nearest road increased. Giant pangolin presence records were mainly found at distances shorter than 100 meters from the park interior to the nearest roads, and the probability of finding a giant pangolin close to road sites was almost zero (Fig. 10 A). Similarly, the probability of finding giant pangolin decreased with increasing Euclidean distance from the park's interior to villages. Giant pangolin occurrence signs were primarily encountered at distances less than 2000 meters to villages, with a peak recorded around 1000 meters (Fig. 10B). Beyond a distance of 2000 meters, the probability of giant pangolin occurrence decreased drastically to almost zero.

IV. DISCUSSION

Suitable habitat area and habitat preference

The study area exhibited a significant presence of suitable habitat for giant pangolins, with a preference shown for primary forests over other types such as gallery, secondary and swamp forests, in descending order. This indicates that even within suitable areas, giant pangolins tend to thrive more in primary forests. This finding aligns with previous research suggesting that giant pangolins have a preference for forested habitats. For example, Suwal et al. (2020) found that pangolin burrows in general were most frequently observed in forested habitats with mixed vegetation and canopy cover in Nepal. Similarly, Dhami et al. (2023) reported that the majority of Chinese pangolin burrows were located in areas with moderate to high canopy and ground cover within forested habitats. In contrast to these findings, a study conducted in Mbam et Djerem National Park in central Cameroon (Mouafo et al., 2023) found that most habitats were unsuitable for giant pangolin, with suitable habitats scattered across densely forested areas, ecotones, and savannas. The disparity in results could suggests that Mbam et Djerem National Park is experiencing more intense anthropogenic encroachment compared to CMNP.

Percent contribution of environmental variables to the MaxEnt model

Aspect followed by slope contributed highest to giant pangolin habitat suitability suggesting that specific slope directions and inclination of the terrain plays a significant role in giant pangolin habitat suitability in the study area. Soil organic carbon was the most important soil variable while pH index in water solution had the least impact. Soil organic carbon content has been linked to soil fertility and food availability for organisms like insects that pangolins prey on. Our findings emphasize the importance of landscape characteristics (aspect, slope) and soil composition (particularly soil organic carbon) in determining suitable habitat for pangolins and giant pangolin in particular. At Mbam et Ndjerem National Park, soil pH also contributed to the suitability of giant pangolin habitats.

Probability of pangolin occurrence with environmental variable

Geophysical variables

The probability of giant pangolin signs occurrence increased on southeastern (112.5–157.5°), southern (157.5–202.5°), and western (≥247.5°) aspects. Thapa et al. (2014) reported a similar preference for southwest aspects (150°–250°) in Nangkholyang, Eastern Nepal. Additionally, Dhital et al. (2020) documented a preference for eastern aspects in the Nagarjun Forest of Shivapuri National Park, which aligns with the south-eastern orientation observed in this study. However, these findings diverge from Bhandari and Chalise (2014) and Dhakal (2016), who reported a preference for north-facing slopes in Nepal. Furthermore, Suwal (2011) suggested a random distribution of pangolin burrows.

We recorded most burrows on slopes between 4° and 20°. The probability of finding their giant pangolin burrows decreased with increase in steepness of a given surface area from 20°–60° confirming supporting the work of Wu et al. (2003) attesting that burrowing pangolin species mostly prefer slopes less than 50°. These results corroborate those obtained elsewhere, for example; Shrestha et al. (2021) registered similar results in the low Lands of Nepal. Furthermore, Karawita et al. (2018) and Sharma et al. (2020) reported that pangolin burrows were mostly encountered on slopes of less than 30° and 15°–22° respectively. The higher preference of less sloppy areas by pangolins might be due to easy movement (Achrya et al., 2021) and digging (Dorji and Dorji, 2020) in those areas coupled with minimum rain-mediated soil erosion. These results however contradict those reported by Wu et al. (2004) and Suwal et al. (2020), which stipulated that pangolins prefer to make their burrows on slopes of 30–60° and 30–50°, respectively. This could be explained from the fact that steeper slopes (30–60°) could maintain stable temperatures inside burrows and ensure the availability of termites (Wu et al., 2003).

Soil variables

Our results revealed a positive correlation between giant pangolin sign occurrence and soils with higher sand, clay, and silt content. Several factors potentially explain this association. Firstly, sand particles (diameter: 0.05mm–2mm) promote soil aeration, fostering plant growth and creating a suitable habitat for ground-dwelling termites and ants (Difouo et al., 2021). These prey species likely constitute a significant portion of the pangolin's diet, thus explaining the increased giant pangolin sign incidence in areas with sandier soils. Secondly, silt particles (diameter: 0.002-0.06mm) possess a fine texture that readily mixes with water to form a loose, easily excavated substrate (The Constructor, 2020). This characteristic facilitates burrowing by pangolins in search of prey or refuge. Finally, clay particles are the finest soil component (diameter < 0.002mm), originating from the chemical decomposition of rocks (Cory, 2020). These minuscule, cohesive particles may also contribute to burrowing suitability or reflect broader environmental conditions that favor pangolin activity.

The probability of giant pangolin occurrence increased in soils with lower soil organic carbon (SOC) concentrations. Zhang et al. (2021) suggested a link between high soil pH (8.5–9.0) and elevated SOC content. However, existing research contradicts this perspective. For example, Mouafo et al. (2023), Rai et al. (2019), and Shrestha et al. (2021) reported a giant pangolin burrow mostly occurred in moderately acidic soils (pH: 5.25–5.52). This apparent preference for moderately acidic soils with lower SOC might be attributable to optimal nutrient availability for plant growth. Studies by Chao et al. (2020), Irshad et al. (2015), Mugerwa et al. (2011), Jacquemin et al. (2012), and Staab et al. (2014) suggest that reduced SOC content promotes conditions favorable for the establishment and proliferation of ground-dwelling termites and ants, a primary food source for pangolins. Consequently, giant pangolins might preferentially select burrowing sites in soils with lower SOC content due to the indirect benefit of increased prey availability associated with moderate acidity (pH: 5.25–5.52).

The probability of giant pangolin occurrence peaked in soils with moderate to high coarse fragment concentration (110–180 cm^3/dm^3). This observation aligns with previous research on giant pangolin burrows by Mouafo et al. (2023). The prevalence of large burrows in this study further suggests a dominance of giant pangolins in the studied area. The preference for moderate to high coarse fragment concentrations might be linked to the giant pangolin's dietary habits. For example, Difouo et al. (2021) showed that pangolins primarily consume ground-dwelling termites and ants. Soils with such fragment concentration likely provide suitable burrowing grounds for these prey species, indirectly influencing giant ground pangolin distribution. Furthermore, coarse fragments play a significant role in soil and water management (Khetdan et al., 2017; Zhang et al., 2019). They can significantly enhance drainage and aeration within the soil matrix, potentially leading to increased soil biodiversity. This, in turn, could contribute to a richer prey base for insectivorous pangolins.

Giant pangolin sign occurrence increased in soils with lower bulk density (<120 kg/m^3). Conversely, the number of giant pangolin signs decreased significantly with increasing bulk density (≥120 kg/m^3). The observed association likely reflects the presence of a preferred prey source, ants, in less dense soils. Zhong et al. (2021) suggested that ant burrowing activities contribute to the reduction of soil bulk density. Lower bulk density is associated with several potential benefits for ant populations. As reported by Evans et al. (2011), soils with lower bulk density exhibit improved water infiltration capabilities. Dauber et al. (2001) linked reduced bulk density to elevated soil microbial activity. This, in turn, can lead to increased microbial activity that promotes the breakdown of organic matter, potentially leading to higher soil nitrogen availability, which can benefit plant growth (Dauber et al., 2001).

Our results revealed that the probability of giant pangolin occurrence increased as soil pH increased from 0 to 4.6 indicating that giant pangolin thrives better in acidic soils. These results support those obtained by Mouafo et al. (2023) in Mbam et Djerem, and those of Shrestha et al. (2021) obtained in the low land of Nepal. Rai et al. (2019) also obtained similar results in the Community Forests of Dolakha District, Nepal. Soil pH and nutrient availability directly correlates with ant and termite abundance (Davies et al., 2003, Mugerwa et al., 2011; Roisin and Leponce, 2004). Soils with very low pH values have limited nutrients necessary for plant growth and therefore adequate food resources which tend to constrain survival of termites and ground dwelling ants (Chao et al., 2020, Irshad et al., 2015; Mugerwa et al., 2011; Jacquemin et al., 2012; Staab et al., 2014). The inadequate food availability drastically restricts the distribution of giant pangolins in particular (Hoffmann et al., 2020).

Habitat variables and anthropogenic variables

Our results revealed that the probability of giant pangolin signs occurrence was more in the primary forest. This might be because primary forest has a relatively denser canopy compared to other forest types. For example, Rai et al. (2019) and Suwal et al. (2020) in Nepal reported that pangolins prefer habitats with medium canopy coverage than forests that are too sparse canopy. The probability of giant pangolin sign occurrence decreased as Euclidian distance from park interior to nearest road increased and as Euclidian distance from park to villages increased. Giant pangolin occurrence was mostly observed at distances greater than 100m from nearest road and greater than 1000m from settlements as was equally the case in Nepal (Katuwal et al., 2017; Wu et al., 2003). This might be attributed to more anthropogenic activities like livestock rearing and collection of fallen logs of wood as these are common human activities around the boundaries of our study area. This has been observed in certain places to cause pangolins to abandon their burrows (katuwal et al., 2017). In contrast, Sharma et al. (2020) recorded 51% of occurrence plots within a 1000m distance from settlement areas. Similarly, a study by Karawita et al. (2018) revealed that burrow distribution was greater in an area with greater human disturbance (<200m) and decreased with increased distance from human settlement.

We did not include in our model other environmental variables reported to have an impact on giant pangolin suitability such as Advanced vegetation index, Euclidian distance to the park's boundaries and Euclidian distance to nearest river (Mouafo et al., 2023; Zhong et al., 2021), and elevation (Mouafo et al., 2023; Zhong et al., 2021; Waseem et al., 2020). We did not take into consideration climatic variables to test model performance such as rainfall and temperature as was done elsewhere (Zhong et al., 2021). These and more will be considered in our subsequent field surveys.

V. IMPLICATIONS FOR CONSERVATION AND RECOMMENDATIONS

We have demonstrated that a significant portion of the Campo Ma'an National Park (CMNP) is suitable habitat for giant pangolin and that it mostly prefers primary forests where the majority of occurrence signs were found. However, giant pangolin also inhabits other forest types such as gallery and secondary forests to a lesser extent. Although the model indicates that a large part of the landscape is suitable, it is recommended to focus conservation efforts on primary forests for maximum effectiveness. Additionally, our findings indicate that the likelihood of giant pangolin presence decreases as distance from primary forests increases and as proximity to roads and villages increases. Conservation strategies should focus on maintaining or restoring connectivity between suitable giant pangolin habitats to facilitate movement and gene flow among populations. This could include creating wildlife corridors, implementing road planning measures to reduce habitat fragmentation, and promoting sustainable land use practices in buffer zones surrounding protected areas. The existence of roads and villages near the Campo Ma'an National Park (CMNP) indicates a higher likelihood of human-wildlife conflict, such as poaching, habitat destruction, or retaliatory killings. Conservation efforts should involve engaging with communities and implementing outreach programs to increase awareness about pangolin conservation in general as well as promoting alternative livelihood activities that reduce dependence on natural resources. Furthermore, implementing measures to mitigate conflicts between humans and pangolins, such as providing incentives for coexistence and developing strategies for conflict resolution, should be prioritised. Integrating environmental considerations into land use planning and natural resource management policies is crucial for prioritising the protection of critical giant pangolin habitats. The identification of geophysical and soil variables as major determinants of giant pangolin habitat suitability emphasises the need for incorporating habitat connectivity into landscape-level planning efforts. Finally, it is crucial to continue monitoring and researching giant pangolin populations and their habitats to evaluate the effectiveness of conservation efforts. This may require ongoing surveys to monitor giant pangolin distribution and abundance, research to identify additional factors that affect giant pangolin habitat suitability, and collaboration with local communities and stakeholders to gather information on giant pangolin ecology and behaviour. Despite potential direct and indirect interactions between aardvark and giant pangolin (Morin et al. 2020), it is thought that giant pangolin may sometimes use abandoned aardvark burrows for resting (Hoffmann et al., 2020). The correlations between their behaviors remain unclear; therefore it would be worth investigating the interactions between the two species to better understand their ecological interactions for improved planning of giant pangolin conservation endeavours.

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CONTRIBUTIONS

NKK, MBT, and MDC conceived and designed the experiments. NKK conducted fieldwork. NKK, HBN and CF developed the methodology. NKK, MBT and CF edited the work.

DECLARATION OF CONFLICTING INTERESTS

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

DATA AVAILABILITY

The datasets generated and analyzed for the current study are available from the corresponding author upon reasonable request.

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