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Modeling Habitat Suitability for African Elephants (*Loxodonta Africana*) in a Savannah Ecosystem, Kenya

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Abstract

Effective conservation of African elephants requires clear understanding of the environmental factors influencing their habitat distribution, particularly in the face of climate change. This study assessed current and future habitat suitability for African elephants in the Nasalot-South Turkana-Kerio Valley ecosystem. The Maximum Entropy (MaxEnt) model was developed using 133 spatially independent occurrence records, 12 non-correlated environmental variables, a Linear–Quadratic feature combination, and a regularization multiplier of 3.5. Species occurrence data were obtained from field surveys and spatial data on various environmental variables were sourced from multiple online sources, including WorldClim, United States Geological Survey (USGS), ASTER Global DEM, HydroSHEDS and OpenStreetMap. Bias correction involved removing redundant records, spatial filtering of occurrence points, selecting background points, and eliminating highly correlated variables. Area Under the Curve (AUC) was used to evaluate the model. Model performance was high (AUC = 0.868 ± 0.006), with Precipitation of the Coldest Quarter *(bio_19) contributing the most (62.5%), followed by land use/land cover (14.6%). Results indicate that currently, low suitability habitats dominate the landscape (~41.10%) while highly suitable habitats occupy only ~8.71%. Under future climate scenarios SSP245 and SSP585, unsuitable habitats are projected to expand significantly, covering between 67.09% and 70.93% of the region. In comparison, moderate and low suitability classes are expected to decline by 53.73% and 68.21%, respectively. The findings indicate significant shifts in elephant habitat suitability under future climate scenarios, underscoring the urgent need for adaptive conservation.*

Keywords: *Climate change, Distribution, MaxEnt, Modeling, Variables*

Introduction

The African elephant, a keystone species and an ecosystem engineer, is a vital megaherbivore with profound ecological and socio-economic roles (Pringle, 2008, Campos-Arceiz & Blake, 2011; Haynes, 2012; Ong *et al.*, 2022). However, African elephant populations are increasingly being threatened by anthropogenic pressures, including human population growth, settlement expansion, agricultural encroachment, and other forms of land development (Kioko & Seno, 2011; Okello *et al.,* 2015; Schüßler *et al.,* 2018). Key threats include habitat loss, degradation, and fragmentation; loss of migratory corridors and dispersal areas; poaching and illegal killing; land-use change; and climate change (Kioko & Seno, 2011; Okello *et al.,* 2015; Schüßler *et al.,* 2018). These pressures have intensified human–elephant conflicts, reduced genetic diversity, increased inbreeding, and caused population isolation and local extinctions, ultimately driving widespread declines (Lohay *et al.,* 2020; Chen *et al.,* 2021; IUCN, 2021). According to the IUCN Red List (2021), African savanna elephant populations have declined by at least 60% over the past 50 years, while African forest elephants have declined by more than 86% in just 31 years. The African Elephant Status Report (2016) further estimated a loss of 111,000 individuals within a decade, leaving only about 415,000 elephants on the continent. Consequently, the African elephant is now listed as Critically Endangered on the IUCN Red List of Threatened Species (IUCN, 2021).
Also, African elephant habitats are increasingly under threat from a range of anthropogenic and environmental pressures such as urban expansion, infrastructure development, and land use changes, which have led to fragmentation and significant reductions in the extent of their current suitable habitats (Dejene *et al.*, 2021; Akala *et al.*, 2023; Jeza & Bekele, 2023). Dejene *et al.* (2021) reported that only 17.1% of the African continent is currently highly suitable for elephants, while 56.6% is unsuitable under present climatic conditions. Their projections indicate a decline in highly suitable habitats by 51.3% under RCP 4.5 by 2050 and by 67.6% under RCP 8.5 by 2070, with losses increasing to 74.5% and 85.9% under the respective scenarios by late Century.

Despite growing interest in species distribution modeling of elephants, such studies remain relatively limited for African elephants across many African landscapes, particularly within Kenya (Williams *et al.*, 2018; Akala *et al.*, 2023; Jeza &

Bekele, 2023). Specifically, no published research to date has focused on modeling current and future habitat suitability of African elephants within the Nasalot-South Turkana-Kerio Valley ecosystem in Kenya, despite its high climatic and biophysical variability and threats such as habitat loss and degradation, species decline and extirpation, reduced wildlife populations, escalating human–wildlife conflicts, vegetation loss, soil erosion, and climate change (Togoch *et al.*, 2018; Boitt *et al.*, 2020; Wildlife Research and Training Institute (WRTI) and the Kenya Wildlife Services, 2021). This study, therefore, addresses the knowledge gap by modeling and mapping current and future habitat suitability for African elephants, while identifying key environmental drivers in this ecologically important yet understudied ecosystem.

Materials and Methods

Study Site Description

The study was conducted in the Nasalot–South Turkana–Kerio Valley Ecosystem in northwestern Kenya, spanning Elgeyo Marakwet, Baringo, West Pokot and Turkana Counties (0°61′18″N–2°17′59″N; 35°33′16″E–35°79′11″E) over ~4,700 km² (Figure 1). The area lies within Kenya's semi-arid eco-climatic zone IV (Pratt & Gwynne, 1977), characterized by high mean annual temperatures (~33°C), low and erratic rainfall (≤508 mm), seasonal rains (March–June, June–December), frequent droughts, and high potential evaporation (1,650–2,300 mm. The ecosystem includes four national reserves: Rimoi, Kamnarok, Nasalot and South Turkana. Vegetation comprises riverine forest, bushland, thickets and grasslands; dominated by trees and lianas from Poaceae, Mimosaceae, Acanthaceae, Capparaceae, Lamiaceae and Euphorbiaceae. Key species based on Importance Value Index (IVI) include *Acacia tortilis*, *Acacia mellifera*, *Cynodon nlemfuensis*, *Acacia sayel*, *Ficus sycomorus*, and *Acacia fruticosa* (Kuria, 2001). Vegetation dynamics are driven by rainfall seasonality and land-use changes, with vegetation appearing green during the wet season and sparse during the dry season, exhibiting notable shifts over the period 1986–2006 due to agricultural and population growth (Togoch, 2018). Historically, the area is rich in large mammals, including elephants, buffalo, leopards, giraffes and antelopes, but many species have been locally extirpated, leaving elephants, warthogs, dik-diks, duikers, impalas, and baboons, along with diverse birds, reptiles and insects (Kuria, 2001). Local communities, including the Keiyo, Marakwet, Tugen, Pokot, and Turkana, traditionally practiced pastoralism but are increasingly adopting sedentary farming. The ecosystem is considered disturbed due to persistent security challenges.

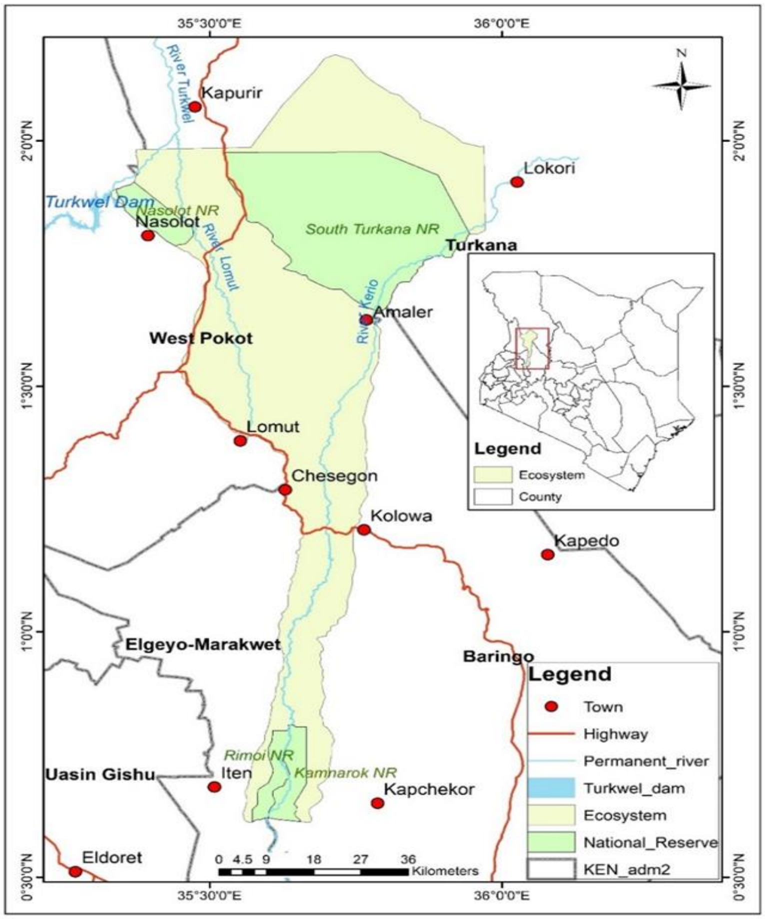

Figure 1: Map of the Nasalot-South Turkana-Kerio Valley ecosystem

Research Design

An exploratory research design was employed to assess environmental influences on African elephant habitat suitability. This approach is well-suited to ecological studies with limited prior hypotheses or complex, nonlinear species–environment relationships (Guisan & Zimmermann, 2000; Creswell, 2014). It supports presence-only modeling techniques, such as MaxEnt, allowing empirical estimation of species–environment relationships and prediction of current and future suitable habitats (Clark, 2017). The design also facilitates evaluation of variable contributions and ecological niche constraints, informing conservation and habitat management in dynamic landscapes.

Species Occurrence Data Collection and Preparation

African elephant's occurrence data were obtained secondarily from previously conducted field surveys. These surveys, conducted between 2011 and 2022, included both foot and vehicle patrols and were based on direct sightings and indirect evidence of elephant presence, such as footprints (tracks), dung, feeding marks and other signs of herbivory. To enhance spatial and temporal coverage, data from the 11 years were pooled and compiled into a single dataset for use in species habitat suitability modeling. The surveys conducted via aerial, foot and vehicle methods were primarily designed to detect presence-only data, not absence. As is typical in elephant monitoring, sampling efforts were focused on areas with likely or confirmed species occurrence. For each occurrence point, the following information was extracted: a unique species identification code, the taxonomic name of the species, and the geographic coordinates (latitude and longitude) of the observed or inferred location (Scheldeman *et al.,* 2010). The collected dataset comprised 4,092 presence-only records, suitable for MaxEnt modeling approach, which is designed to handle such data limitations. Redundant species records were removed, and spatial autocorrelation using Global Moran's Index (Moran's I) (Moran, 1950) in ArcGIS version 10.8 was performed on the collected species occurrence dataset before and after correcting for sampling biases through the spatial filtering method in

ArcGIS. A total of 133 species occurrence records, each separated by at least 1.5 km and showing no clustering, were selected for modeling.

Predictor Environmental Variables

A total of 27 environmental predictor variables were selected for their demonstrated relevance, accessibility from reputable sources, and frequent application in modeling African elephant habitat suitability and spatial distribution (Williams *et al.,* 2018; Akala *et al.,* 2023; Jeza & Bekele, 2023). Environmental variables consisted of 19 bioclimatic variables, three topographic variables (elevation, slope, and aspect), three distance variables (Euclidean distance to roads, waterbodies, and human settlements), one vegetation variable (NDVI) and one land use/land cover variable. Nineteen (19) bioclimatic variables covering the period from 1970 to 2000 were acquired from WorldClim version 2 at 30 arc-second spatial resolution (Fick & Hijmans, 2017; http://www.worldclim.org). For future projections, the study used downscaled and calibrated bioclimatic data from the CMIP6 General Circulation Models (GCMs), specifically from the Canadian Earth System Model version 5 (CanESM5). Two Shared Socioeconomic Pathways (SSPs), SSP245, representing a "middle of the road" scenario, and SSP585, representing a fossil fuel–driven development scenario, along with averages of monthly data values for the periods 2041–2060 and 2081–2100 (Fick & Hijmans, 2017; http://www.worldclim.org), were used to project the potential future habitat suitability for African elephants. Multispectral remote sensing images, United States Geological Survey (USGS) Landsat-8 Operation Land Imager (OLI) Collection 2, level 1 for the year 2024, were used to generate six land use/land cover (LULC) categories and to calculate spectral indices for Normalized Difference Vegetation Index (NDVI) at 30 m spatial resolution. Topographic data obtained from ASTER Global DEM website (http://gdem.ersdac.jspacesystems.or.jp/) with a spatial resolution of 30 m was used to generate elevation, slope and aspect. Waterbodies data obtained from the HydroSHEDS website (https://www.hydrosheds.org/) were used to prepare the Euclidean distance to waterbodies shapefile in meters. Road network data and Human settlement data acquired from the OpenStreetMap website (https://www.openstreetmap.org/) were used to prepare shapefiles of Euclidean distance to roads and human settlements in meters. To ensure consistency across datasets, a spatial resolution of 30 m was adopted as the final spatial scale for modeling. All raster data were clipped to the extent of the study area, projected to the WGS 1984 coordinate system, and converted to ASCII data format. To address multicollinearity and reduce dimensionality, predictor variables were screened using Pearson's correlation coefficients, and percentage contributions were calculated using the Jackknife analysis, as described by Zhou *et al.* (2021). Variables with contributions > 0.3% and correlation coefficients $-0.8 < r < +0.8$ were retained for the final model (Zhou *et al.* (2021). Consequently, a total of 12 predictor environmental variables were retained for the optimization of the MaxEnt model and construction of the final habitat suitability model (Table 1).

Table 1: Preselected environmental variables for modeling habitat suitability for African elephants

Predictor variable	Code	Unit
Bioclimatic		
Mean Monthly Diurnal Range	bio_2	°C
Isothermality	bio_3	index
Temperature Seasonality	bio_4	°C
Precipitation Seasonality	bio_15	mm
Precipitation of the Coldest Quarter	bio_19	mm
Biophysical		
Elevation	-	meters
Slope	-	degrees
Aspect	-	degrees
Euclidean distance to waterbodies	waterbodies	meters
Vegetation		
Normalized Difference Vegetation Index	NDVI	index
Anthropogenic		
Land use/land cover	LULC	categories

Euclidean distance to roads	roads	meters

Data Analysis

MaxEnt version 3.4.4 (Phillips *et al.,* 2006; Phillips & Dudík, 2008) was used to model habitat suitability for African elephants, with the optimized model developed using 133 spatially independent occurrence points, 12 non-correlated environmental variables, a Linear (L) and Quadratic (Q) feature combination, and a regularization multiplier of 3.5. Feature combinations and regularization multipliers were evaluated and selected using the ENMeval package in R (Muscarella *et al.,* 2014), which incorporates the recommendations of Radosavljevic and Anderson (2014) through diverse training–testing partitioning methods and tuning options. MaxEnt was configured to generate response curves and to perform Jackknife tests of variable importance. Species occurrence data were randomly divided into two sets: 70% as training data (for calibrating the species models) and 30% as testing data (for evaluating the models) (Phillips *et al.,* 2006; Budhathoki *et al.,* 2023; Jeza & Bekele, 2023). The model was run with 10-fold replication, 10,000 background points, and 5,000 iterations.

The MaxEnt model was evaluated using a threshold-independent Area Under the Curve (AUC) analysis of the Receiver Operating Characteristic (ROC) (Phillips *et al.,* 2006). The AUC values range from 0 to 1, with >0.9 indicating excellent performance, 0.8–0.9 very good, 0.7–0.8 good, 0.6–0.7 fair, and ≤0.6 poor performance (Swets, 1988, Duan *et al.,* 2014; Mouafo *et al.,* 2023; Elbahi *et al.,* 2024). MaxEnt prediction rasters were classified in ArcGIS using the 10th percentile training presence cloglog threshold and refined manually into four categories: unsuitable (<10th percentile), low suitability (≥10th percentile to <0.4), moderate suitability (≥0.4 to <0.6), and high suitability (≥0.6 to ≤1). The abundance of current and future suitable habitat categories for African elephants and their preferred forage plants was estimated by calculating the area (km²) and proportion (%) of each category. Raster files of climate scenarios were projected to WGS 1984 UTM Zone 37N, converted to polygons using the raster-to-polygon tool in ArcGIS 10.8, and analyzed with the calculation function to obtain areas and proportions. Change analysis was conducted by converting MaxEnt-derived habitat suitability maps for current and future SSP245 and SSP585 scenarios (2041–2060 and 2081–2100) into polygons in ArcGIS, and applying intersection and geometry calculations to quantify spatial shifts in habitat categories by area (km²) and proportion (%).

Results and Discussions

Maxent Model Performance and Validation

Figure 2 shows the test omission rate and predicted habitat suitability area for African elephants across cumulative thresholds, averaged over ten MaxEnt runs. There is a close alignment between the observed (green) and predicted (black) omission rates, with consistent model predictions indicated by blue (area) and orange (omission) lines.

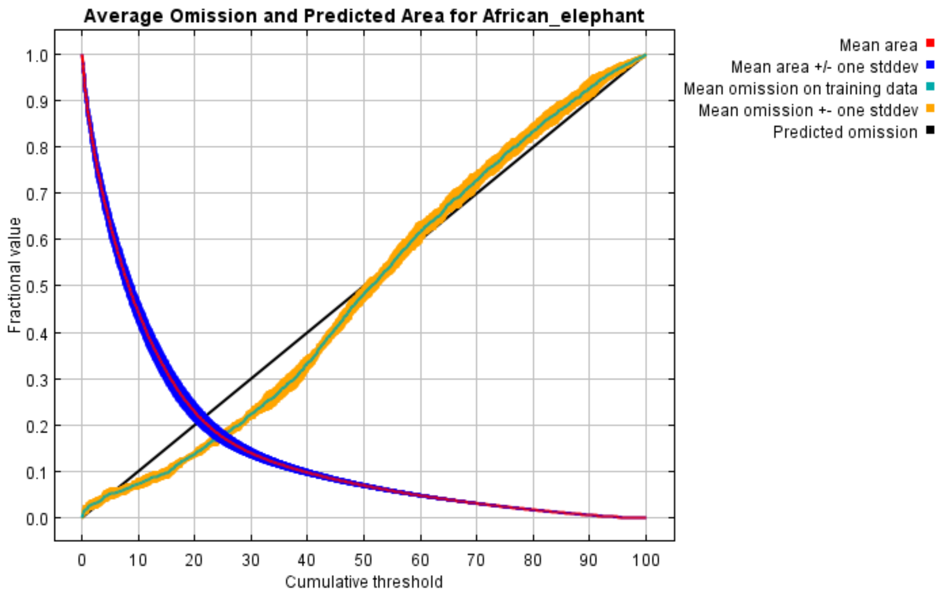

Figure 2: Test omission rate and predicted habitat suitability for African elephants

Figure 3 presents the ROC curve for the predicted suitable habitat of African elephants. The average test AUC across 10 replicate MaxEnt model runs was 0.868 ± 0.006, substantially exceeding the random prediction benchmark of 0.5. This indicates strong model performance in distinguishing suitable from unsuitable habitats.

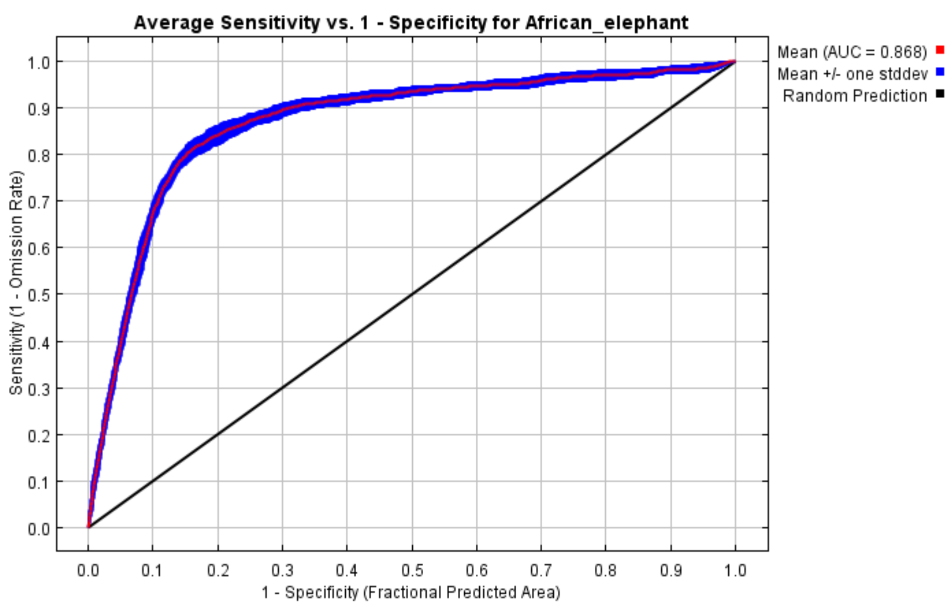

Figure 3: Receiver Operating Characteristic (ROC) curve for predicted habitat suitability of African elephants

Spatial Distribution Pattern of Potential Current Suitable Habitats for African Elephants

Figure 4 illustrates the current habitat suitability map for African elephants, derived from MaxEnt model outputs and classified into four categories based on a cloglog threshold of 0.1532: unsuitable (<0.1532), low (≥0.1532–<0.4), moderate (≥0.4–<0.6), and high (≥0.6–≤1.0) suitability. The spatial distribution of suitability categories varied across the study area. Highly suitable habitats were concentrated in the southwestern region, particularly within Rimoi and Kamnarok National Reserves. Moderate suitability areas occurred adjacent to highly suitable habitats, primarily in the southeastern region. Low suitability habitats were located centrally, forming a transitional zone between southern suitable areas and the northern unsuitable zones. Unsuitable habitats dominated the northern region, including Nasalot and South Turkana National Reserves.

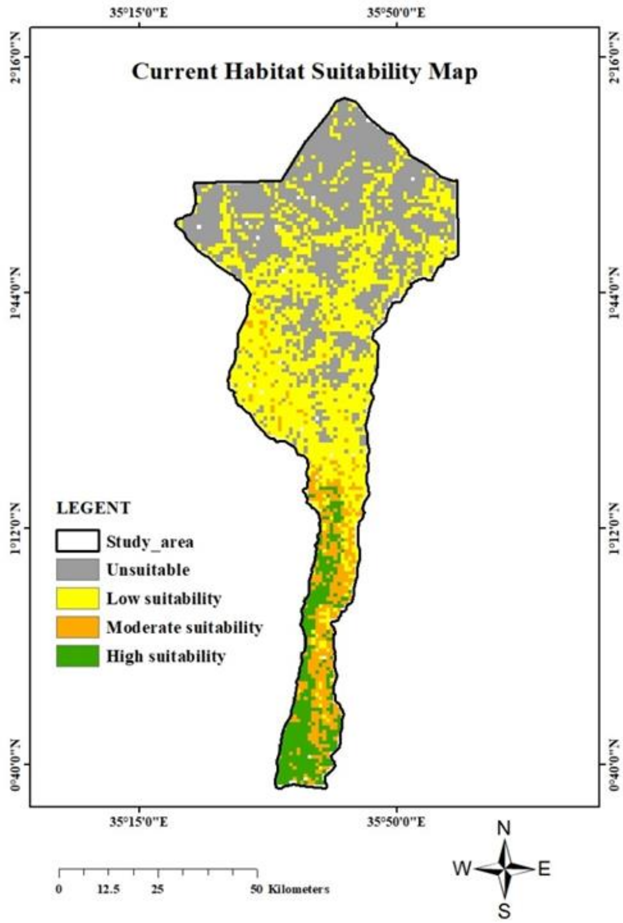

Figure 4: Current habitat suitability map for African elephants

Abundance of Potential Current Suitable Habitat for African Elephants

Table 2 presents the area (km²) and proportion (%) of land occupied by various habitat suitability categories for African elephants under the current scenario. Low suitability habitats occupied the largest share, covering 1,931.59 km² (41.09%) of the total area. The remaining categories, unsuitable, moderate, and highly suitable habitats, each occupied between 409.37 km² and 1931.59 km².

Table 2: Area (km²) and proportion (%) of land occupied by various habitat suitability categories for African elephants under current conditions

Suitability category	Area (km^2)	Proportion (%)
Unsuitable habitats	1918.68	40.82
Low suitability	1931.59	41.10
Moderate suitability	440.37	9.37
High suitability	409.37	8.71
TOTAL	**4700.36**	**100**

Spatial Distribution Pattern of Potential Future Suitable Habitats for African Elephants

Figure 5 displays habitat suitability maps for African elephants under future climate scenarios (SSP245 and SSP585) for the periods 2041–2060 and 2081–2100. The maps, derived from MaxEnt model outputs and classified into four categories using the 10th percentile training presence cloglog theshold, show spatial variation in habitat suitability across the study area. Highly suitable habitats were concentrated in the southwestern region, particularly in areas of both Rimoi and Kamnarok National Reserves. In contrast, unsuitable habitats dominated the northern areas, including Nasalot and South Turkana National Reserves. Moderate and low suitability areas were primarily distributed between these zones of high and low habitat suitability, indicating transitional habitat conditions.

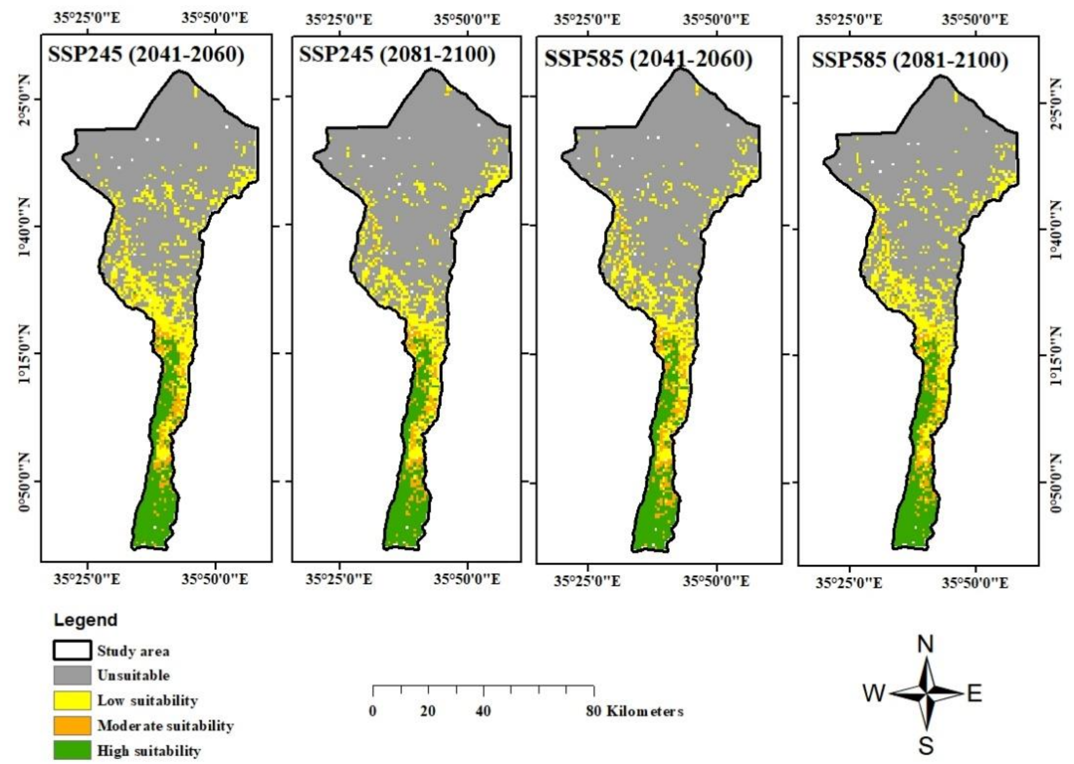

Figure 5: Future habitat suitability for African elephants under climate change scenarios

Abundance of Potential Future Suitable Habitats for African Elephants

Table 3 presents the projected area (km²) and proportion (%) of land occupied by different habitat suitability categories for African elephants under future climate scenarios (SSP245 and SSP585) for the periods 2041–2060 and 2081–2100. The results show a consistent trend toward increasing habitat unsuitability, with unsuitable habitats occupying the largest share of the landscape across all scenarios, ranging from 67.09% to 70.93%. In contrast, low, moderate, and high suitability habitats each covered between 4.34% and 16.32% of the total area, indicating a projected significant reduction in suitable habitat availability over time.

Table 3: Area (km²) and proportion (%) of land occupied by each habitat suitability category for African elephants under future climate change scenarios

Scenario	Period	Suitability category									
		Unsuitable		Low		Moderate		High		Total	
		km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Current	1995–2000	1918.68	40.82	1931.59	41.10	440.37	9.37	409.37	8.71	4700.36	100.00
SSP245	2041–2060	3153.24	67.09	767.10	16.32	203.76	4.34	576.25	12.26	4700.36	100.00
SSP245	2081–2100	3333.95	70.93	614.05	13.06	210.16	4.47	542.12	11.53	4700.30	100.00
SSP585	2041–2060	3303.53	70.28	638.95	13.59	221.28	4.71	536.61	11.42	4700.36	100.00
SSP585	2081–2100	3195.65	67.99	747.74	15.91	212.98	4.53	543.98	11.57	4700.36	100.00

Key Environmental Determinants of the Current and Projected Distribution and Abundance of Suitable Habitats for African Elephants

Percentage contribution and permutation importance. Table 4 summarizes the relative importance of environmental variables used in the MaxEnt model to predict suitable habitats for African elephants, expressed as percentage contribution and permutation importance. Precipitation of the Coldest Quarter (bio_19) was the most influential variable, with the highest percentage contribution (62.5%) and permutation importance (53.3%). Land Use/Land Cover (LULC) was the second most important, contributing 14.6% by percentage and less than 10% by permutation. Combined, bio_19 and LULC accounted for 77.1% of the model's predictive contribution. All remaining variables individually contributed less than 10%, highlighting the dominant role of a few key predictors in shaping habitat suitability.

Table 4: Predictor environmental variables and their contributions to the MaxEnt model for African elephants

Predictor Variable	Percentage contribution (%)	Cumulative contribution (%)	Permutation importance (%)
Precipitation of the Coldest Quarter (bio_19)	**62.5***	62.5	53.3
Land use/land cover (LULC)	**14.6***	77.1	4.4
Euclidean distance to waterbodies (waterbodies)	6.2	83.3	6.2
Mean Diurnal Range (bio_2)	5.2	88.5	0
Temperature Seasonality (bio_4)	4.0	92.5	18.1
NDVI	2.6	95.1	1.8
Aspect	2.3	97.4	5.7
Euclidean distance to roads (roads)	1.5	98.9	0.6
Isothermality (bio_3)	0.8	99.7	8.0
Elevation	0.1	99.8	1.8
Precipitation Seasonality (bio_15)	0.1	99.9	0.1
Slope	0.1	100	0

Jackknife analysis of regularized training gain for African elephants. Figure 6 presents the Jackknife analysis of regularized training gain for environmental variables used in the MaxEnt model to predict current suitable habitats for African elephants. The regularized training gain using all variables was approximately 1.1 (red bar), serving as a baseline for comparison. When used individually (blue bars), Precipitation of the Coldest Quarter (bio_19) yielded the highest gain

(~0.73), followed by Mean Diurnal Range (bio_2) at ~0.45, while other variables contributed less than 0.03. Omitting bio_19 from the model (green bar) reduced the gain to ~0.92, more than the exclusion of any other variable.

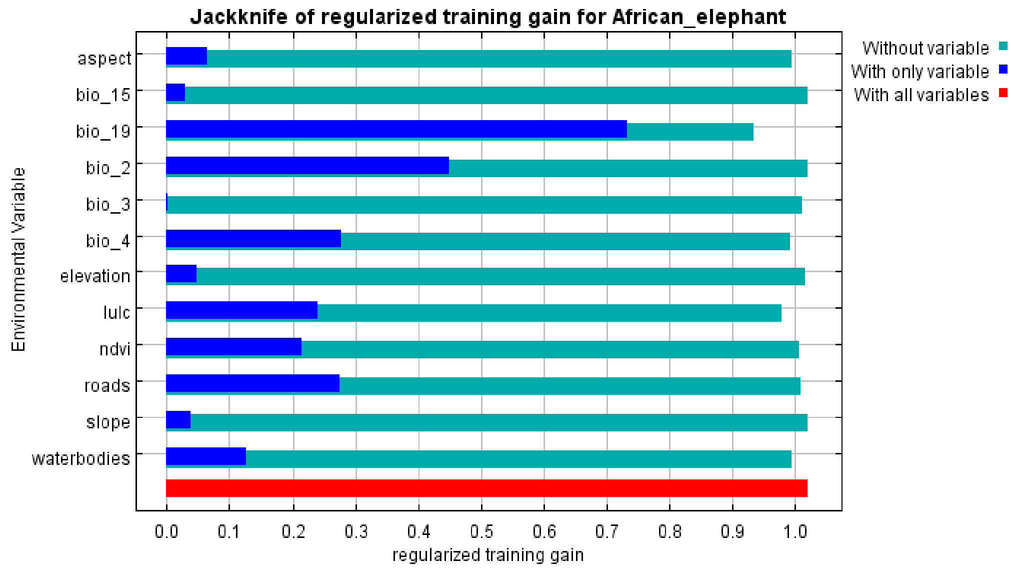

Figure 6: Jackknife analysis of regularized training gain for African elephants

Maxent Marginal Response Curves for the Selected Predictor Environmental Variables

Figure 7 presents MaxEnt marginal response curves showing the probability of suitable habitat for African elephants with selected environmental predictor variables, based on cloglog output averaged over 10 MaxEnt runs. The probability varied with each variable, with Precipitation of the Coldest Quarter (bio_19), the most influential predictor, exhibiting a sigmoidal response. Habitat suitability increased with bio_19, peaking at approximately 350 mm, after which further increases did not enhance suitability. Suitability also varied across land use/land cover types, with the highest probabilities observed in woodland (0.85), followed by built-up areas and shrubland (both 0.64), waterbodies and agricultural areas (both 0.62), while bareland showed a moderate suitability probability of 0.40.

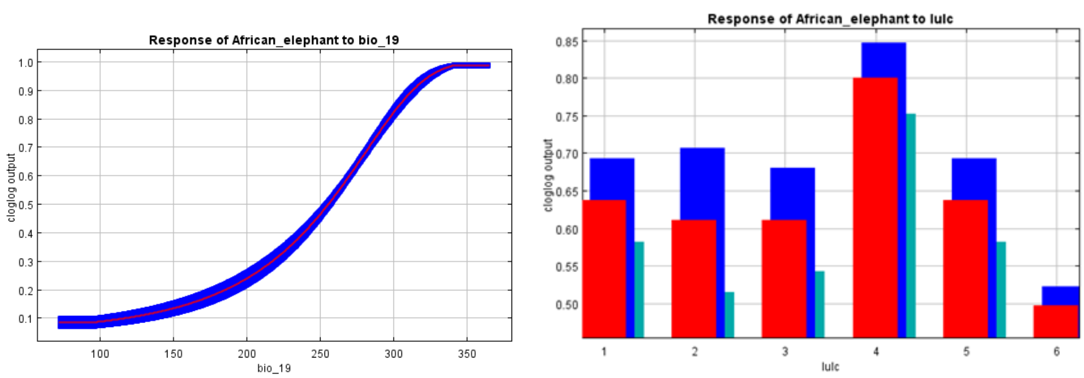

Figure 7: MaxEnt marginal response curves for the key predictor environmental variables for African elephants
NB: LULC categories: Built-up Area (1), Waterbody (2), Agriculture (3), Woodland (4), Shrubland (5), and Bareland (6).

Potential Impacts of Climate Change on Habitat Suitability for African Elephants under Climate Change Scenarios (SSP245 And SSP585) across Future Time Horizons (2041–2060 and 2081–2100)

Table 5 presents the projected changes in area (km²) and proportion (%) of suitable habitats for African elephants under future climate scenarios. The results reveal significant shifts, particularly in unsuitable and low-suitability habitats, with unsuitable habitats increasing by 64.34% to 73.76% and low suitable habitats decreasing by 60.29% to 68.21%.

Table 5: Area (km²) and proportion (%) of change in potential future suitable habitats for African elephants under future climate change scenarios

Scenario	Period	Suitability category							
		Unsuitable		Low		Moderate		High	
		km^2	%	km^2	%	km^2	%	km^2	%
Current	1995–2000	1918.68	40.82	1931.59	41.10	440.37	9.37	409.37	8.71
SSP245	2041–2060	1234.56	64.34	-1164.49	60.29	-236.61	53.73	166.88	40.77
SSP245	2081–2100	1415.27	73.76	-1317.54	68.21	-230.21	52.28	132.75	32.43
SSP585	2041–2060	1384.85	72.18	-1292.61	66.92	-219.09	49.75	127.24	31.08
SSP585	2081–2100	1276.97	66.55	-747.74	61.29	-213.07	51.64	134.61	32.88

Maxent Model Performance and Validation

The MaxEnt model showed strong predictive performance, with an AUC of 0.868 ± 0.006, well above random expectation (0.5). This accuracy reflects the use of spatially filtered occurrence data and uncorrelated, high-contribution environmental variables, optimized with a Linear–Quadratic feature combination and a regularization multiplier of 3.5 to reduce overfitting. Comparable high predictive performance has been reported in habitat modeling studies across Africa and Asia, including China (He *et al.*, 2022; Yang *et al.*, 2022), Nepal (Budhathoki *et al.*, 2023), Thailand (Htet *et al.*, 2021), Ethiopia (Jeza & Bekele, 2023), and Nigeria (Akala *et al.*, 2023).

Spatial Distribution and Abundance of Potential Current and Future Suitable Habitats for African elephants within the Nasalot–South Turkana–Kerio Valley ecosystem

Under current environmental conditions, African elephant habitat suitability exhibited marked spatial variation across the study area. Low-suitability habitats dominated, particularly in the central transitional zone, while highly suitable habitats were limited and largely confined to the southern region, especially within Rimoi and Kamnarok National Reserves. This pattern indicates that much of the landscape provides only marginally suitable environments, with optimal habitats restricted in extent and distribution, likely due to factors such as reduced precipitation during the coldest quarter and LULC dynamics. The confinement of high-quality habitats to protected areas underscores their critical role in sustaining elephant populations, while areas outside reserves may lack sufficient water and forage or experience high human disturbance. Such spatial disparities are likely to influence elephant movement, intensify pressure on limited high-quality habitats, and raise concerns about habitat connectivity and long-term population viability.

The observed spatial distribution aligns with previous studies. Uneven habitat suitability linked to precipitation, forest cover, land-use change, elevation, and water availability has been reported in China (He *et al.*, 2022; Yang *et al.*, 2022), Nepal (Budhathoki *et al.*, 2023), and Myanmar (Htet *et al.*, 2021). Similarly, suitable habitats typically occupy only a small fraction of landscapes across Nepal, China, India, and Africa, where anthropogenic pressures and environmental factors strongly influence habitat quality (Dejene *et al.*, 2021; Budhathoki *et al.*, 2023; Chen *et al.*, 2023; He *et al.*, 2024; Palei *et al.*, 2024). Seasonal variations further restrict suitable habitats in regions such as Ethiopia and Nigeria (Akala *et al.*, 2023; Jeza & Bekele, 2023).

Future climate projections under SSP245 and SSP585 (2041–2060 and 2081–2100) predict substantial declines in suitable habitats, with northern areas, including South Turkana and Nasalot National Reserves, becoming increasingly unsuitable. Moderately suitable habitats are projected to become scarce, persisting mainly in southern transitional zones. These changes are largely driven by shifts in precipitation during the coldest quarter (bio_19) and LULC, which may create uneven capacities across the landscape to meet elephants' ecological needs (Western, 1975; Owen-Smith & Chafota, 2012; Akala *et al.*, 2023; Jeza & Bekele, 2023; Makati *et al.*, 2023).

These findings align with prior research projecting widespread habitat loss for elephants under future climate scenarios. In Africa, substantial declines in suitable habitats are expected (Mpakairi *et al.*, 2019; Dejene *et al.*, 2021), while Asian elephant ranges in India, Nepal, and Southeast Asia are projected to shrink under climate and land-use change (Kanagaraj *et al.*, 2019; Yang *et al.*, 2022; Budhathoki *et al.*, 2023; Abir *et al.*, 2025), highlighting a global vulnerability of elephant habitats to climate change.

Key Environmental Determinants of the Potential Current and Projected Spatial Distribution and Abundance of Suitable Habitats for African elephants

Among the 12 non-correlated environmental variables, Precipitation of the Coldest Quarter (bio_19) and land use/land cover (LULC) were the strongest predictors of elephant distribution, explaining 62.5% and 14.6% of variation, respectively, and jointly accounting for 77.1% of model performance. These findings reflect elephants' ecological requirements, including high water intake, substantial forage demand, sensitivity to temperature extremes, and avoidance of human disturbance, with preferences for habitats offering abundant precipitation, vegetation cover, permanent water, and gentle topography (Western, 1975; Owen-Smith, 2000; Loarie *et al.*, 2009; Owen-Smith & Chafota, 2012; Gaynor *et al.*, 2018; Schlossberg *et al.*, 2018; Mpakairi *et al.*, 2019; Chibeya *et al.*, 2021; Yang *et al.*, 2022; Chen *et al.*, 2023; Makati *et al.*, 2023; Mlambo *et al.*, 2024).
The strong influence of bio_19 aligns with findings from Asia (Yang *et al.*, 2022) and Africa, where precipitation shapes habitat selection, migration, and home range size (Bohrer *et al.*, 2014; Williams *et al.*, 2018; Benítez *et al.*, 2022). Marginal response curves showed optimal suitability at 250–350 mm, underscoring the role of seasonal water availability in sustaining forage species. Similar precipitation-driven shifts have been observed in Marsabit, Kenya, where elephants move downslope during wet seasons and retreat to evergreen forests in the dry season (Bohrer *et al.*, 2014), and in Omo Forest Reserve, Nigeria, where rainfall-driven vegetation attracts elephants (Loarie *et al.*, 2009; Akala *et al.*, 2023).
Land use/land cover was also a key determinant of habitat suitability. Elephants showed a high preference for waterbodies, woodlands, shrublands, agricultural, and built-up areas, while barelands were less suitable. This reflects selection for vegetation and water resources, alongside occasional use of human-modified landscapes (Blake *et al.*, 2008; Loarie *et al.*, 2009; Wall *et al.*, 2013). In Amboseli, elephants select bushland and woodland for structural heterogeneity and forage (Okello *et al.*, 2015), while in Namibia's arid shrublands they rely on key forage species under resource-limited conditions (Viljoen, 1989). Across southern Africa, tracking studies show extensive use of savannas, forest edges, and grasslands, with wet-season shifts toward woodlands and shrublands (Loarie *et al.*, 2009; Chase *et al.*, 2016).
Barelands, though less suitable overall, support elephant foraging and movement as migratory corridors, especially when near water sources. Sparse herbs and grasses provide forage in the wet season, while their location enhances landscape connectivity (Koirala *et al.*, 2016; Geleta & Mengesha, 2022;). Similar use of barelands has been reported in southern Africa near permanent water (de Beer & Van Aarde, 2008), in Kruger National Park as dry-season foraging grounds (Grainger *et al.*, 2005; Loarie *et al.*, 2009), and in Mali's Gourma region during long-distance migrations (Wall *et al.*, 2013).
High suitability in agricultural and built-up areas likely reflects persistence of traditional migratory routes intersecting human settlements and attraction to calorie-rich crops during resource scarcity, intensifying human–elephant conflict (Togoch, 2018). This pattern has been widely observed across Africa (Hoare, 1999; Sitati *et al.*, 2005; Chiyo *et al.*, 2005; Blake *et al.*, 2008; Graham *et al.*, 2009; Koskey, 2013; Gaynor *et al.*, 2018; Schlossberg *et al.*, 2018; Williams *et al.*, 2018; Mpakairi *et al.*, 2019; Akala *et al.*, 2023). Conversely, elephants often avoid areas with intense human activity, as shown in Zimbabwe, Botswana, Angola, and northern Kenya (Songhurst *et al.*, 2016; Schlossberg *et al.*, 2018; Mpakairi *et al.*, 2019; Mortimer *et al.*, 2021), suggesting that increasing anthropogenic pressure may further constrain habitat use in the study area.

Potential Impacts of Climate Change on Habitat Suitability for African Elephants under Future Climate Scenarios (SSP245 and SSP585) across Future Time Horizons (2041–2060 and 2081–2100).

Projections under SSP245 and SSP585 for 2041–2060 and 2081–2100 indicate a substantial decline in suitable habitats for African elephants, accompanied by an expansion of unsuitable areas, signaling increased vulnerability and potential habitat fragmentation (Mpakairi *et al.*, 2019; Dejene *et al.*, 2021). Climate change is likely to alter key environmental conditions, including water availability, forage, and temperature–precipitation patterns, potentially forcing elephants into human-dominated landscapes and intensifying conflict. These findings are consistent with studies across Africa and Asia, which predict widespread habitat loss for elephants under future climate scenarios, including in Zimbabwe's Hwange National Park (Mpakairi *et al.*, 2019), India and Nepal (Kanagaraj *et al.*, 2019), and Nepal's Madhesh Province (Budhathoki *et al.*, 2023), highlighting the urgent need for adaptive conservation strategies that incorporate climate projections.

Conclusions and Recommendations

African elephants are highly vulnerable to climate change, with current habitats largely of low suitability and future projections (SSP245, SSP585) indicating further declines, particularly in northern protected areas. Precipitation of the Coldest Quarter (bio_19) and land use/land cover were the strongest predictors, explaining 77.1% of habitat variation. Projected climate-driven habitat loss threatens elephant distribution and long-term survival.
Conservation of African elephants should prioritize protection of highly suitable habitats such as Rimoi and Kamnarok Reserves and restoration of degraded areas in Nasalot and South Turkana. Establish and maintain ecological corridors and

buffer zones to secure connectivity and gene flow. Integrate key climatic variables, particularly seasonal rainfall, into planning to safeguard dry-season resources. Protect natural vegetation, regulate land-use change, and promote elephant-compatible agriculture to reduce conflict and ensure safe passage. Engage local communities in adaptive, participatory management to strengthen long-term conservation outcomes.

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