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RESEARCH ARTICLE

HABITAT SUITABILITY AND DISTRIBUTION OF ENDANGERED ETHIOPIAN WOLF (*CANIS SIMENSIS*) AND THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON ITS HABITAT IN THE ETHIOPIAN HIGHLANDS

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ABSTRACT: The habitat of the endemic and endangered Ethiopian wolf and populations have been declining because of climate change, coupled with various anthropogenic disturbances, which has restricted the species in Afroalpine geographic range. Understanding the effects of climate change on its range is vital to promoting effective conservation strategies. We aimed to predict the effects of environmental variables on the suitable spatial distribution of the species, under current and various future climatic scenarios using a Maximum Entropy algorithm (MaxEnt). We used the averages of the three shared socioeconomic pathways: low (ssp126), intermediate (ssp245), and worst (ssp585), developed by the Canadian Earth System Model (CanESM5). We also used the average of the two general circulation models, considering 2050 and 2070. Our results show the maximum temperature of the warmest month and ecoregion had the highest percent contributions to the suitability index, 65.4 and 16.1, respectively. Of the total area of Ethiopia, only 2,779,658 ha was predicted to be a potentially suitable area under current conditions. The projected suitable areas of *C. simensis* under future climate change show an increase, range shifts, fragmentation, and small changes in availability. Our predicted results showed that the species has a small, fragmented suitable habitat. Habitat restoration, reduction of anthropogenic pressures, and climate change mitigation should be emphasized to improve the conservation of *C. simensis*.

Key words/phrases: Afroalpine, Canid, Ethiopian wolf, Habitat contraction and expansion, Species distribution model.

INTRODUCTION

Global biodiversity has faced a variety of threats (Thuiller *et al.*, 2005; Watson *et al.*, 2014), due to the deterioration of ecological systems

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(Leadley, 2010), habitat loss (Sefi Mekonen, 2020), and direct provocation triggered by political instability (Marino, 2003a). These factors directly and significantly impact endangered species by affecting their survival (Thuiller *et al*., 2005). For example, Afroalpine habitats have declined and fragmented (Annissa Muhammed and Eyasu Elias, 2021), shifted (Tariku Mekonnen, 2020), and species are at risk of extinction (Morrison *et al*., 2007; Gordon, 2009).

Climate change resulting from human activities has been rapidly continuing for many decades (Zhu *et al*., 2010; Campos *et al*., 2017). The effects on species include biological and phenological changes, historical range shifts, and reduced range size through space and time (Lenoir *et al*., 2008; Early and Sax, 2011; Bellard *et al*., 2012; Lovari *et al*., 2020). Continued climate change worsens the previously noted habitat loss, resulting in a severe negative effect on the wildlife communities (Graham *et al*., 2016; Carvalho *et al*., 2019; Morelli *et al*., 2020). Understanding the effect of climate change coupled with other stressors on species distribution will help in the formulation of conservation policies to reduce the risks of future biodiversity losses (Aryal *et al*., 2016).

Evaluating habitat suitability is critical for wildlife conservation and management (Meller *et al*., 2014; Su *et al*., 2021). Predicting biodiversity's vulnerability to climate change has become an active field of study (Dillon *et al*., 2010; Gilman *et al*., 2010; Dawson *et al*., 2011). In this regard, species distribution models (SDMs) are powerful tools to understand species ecology, biogeography, conservation biology, and develop conservation strategies (Morrison *et al*., 2007). They are also useful for predicting the impacts of climate change on biodiversity (Dunham *et al*., 2011; Bean *et al*., 2012; Sohel *et al*., 2015; Graham *et al*., 2016). Furthermore, understanding how species have been affected by recent human-mediated landscape transformation is crucial for designing an effective conservation strategy (Khalatbari *et al*., 2018).

The Ethiopian wolf (*Canis simensis*, Ruppell, 1840) is one of the endemic and endangered species of the Canidae family (Macdonald *et al*., 2019). It is distinguished from jackals (*C. aureus*, *C. mesomelas*, and *C. adustus*) by its large size, long legs, and reddish coat with white markings (Sillero-Zubiri and Gottelli, 1994).

Although different studies on Ethiopian wolves have been conducted, habitat suitability analysis as a function of future climate change was overlooked in all Afroalpine ranges except for the population living in the

Bale Mountains National Park (Marino, 2003b), and a recent study on the habitat suitablity under current and future scenarios (Yericho Berhanu *et al*., 2022). We applied a habitat suitability model to investigate ways in which the species responds to its environments at various scales of Afroalpine habitats. Therefore, the present study is aimed to identify the environmental predictors that determine the suitable habitat for *C. simensis* and examine habitat suitability for future conservation implications.

MATERIALS AND METHODS

Study area

Ethiopia is in the tropics (3°–15° N latitude and 33°–48° longitude) (Fig. 1). The geographical diversity of the country ranges from 125 to 4,533 m. a.s.l. The biodiversity includes both the Afrotropical and Palearctic biota due to Ethiopia's connections with the temperate biome in the north and the Arabian Peninsula during the dry glacial period (Asefa Mengesha *et al*., 2020). Most of the Ethiopian highlands are dominated by four identified vegetation types: the Acacia limit at ca 2,730 m, the *Hagenia*, *Juniperus*, and *Olea* montane forest limits at ca 3,200 m, and the *Erica arborea* (Jacob *et al*., 2015). Ethiopia also has approximately 311 mammal species, 55 of which are endemic (Lavrenchenko and Afework Bekele, 2017). Only Afro-alpine and montane habitats in Ethiopia are home to the Ethiopian wolf (Ashenafi Zelalem *et al*., 2005; Marino *et al*., 2010; Marino and Sillero-Zubiri, 2013). Historically, they were found in eastern and southern Ethiopia (Yalden, 1983), but are now locally extinct. The current distribution model research focused on all the Ethiopian highlands, such as Simien Mountains, Abune Yosef, Borena-sayint National Park, Guassa community conservation area, Arsi Mountains National Park, and Bale Mountains National Park.

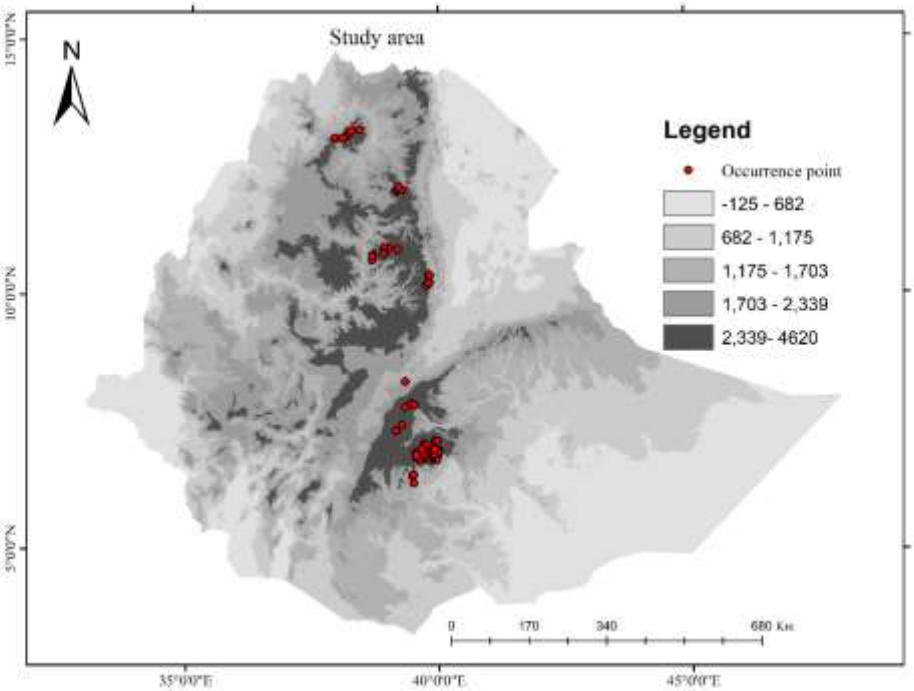


Fig. 1. Location map of the study area with occurrence points of the study species.

Data collection and analysis

Occurrence data

We extracted and assembled a total of 163 occurrence points from our field collection (n = 62), from GBIF (n = 101) GBIF Occurrence Download (https://doi.org/10.15468/dl.mjsbx6), Accessed Date, 20, January 2022) and previous co-authors' published literature (Mesele Yihune and Afework Bekele, 2014; Tariku Mekonnen *et al*., 2019). Initially, we removed the outliers and duplicates. Then, these occurrence points were referenced to ~5 km grid resolution before being used in the final model. As a result, only one occurrence record within a ~5 km pixel was considered valid for model building (Phillips *et al*., 2006). Thus, a total of 106 presence points were used to evaluate the species' suitable habitat and distribution using the Maxent algorithms.

Environmental predictors

We selected 25 environmental predictor variables and further grouped them into three categories: climatic, topography, and landscape. Nineteen bioclimatic data with a 2.5 arc-minute spatial resolution (~ 5 km) were obtained from World Climate Version 2.1 (www.worldclim.org) (Fick and Hijmans, 2017). The current climate from 1970–2000 and future climate scenarios 2050 (average of 2041–2060) and 2070 (average of 2061–2080) were used. We used these to model the effects of future climate change on the habitat suitability of the species using three Shared Socioeconomic Pathways (SSPs): the straightest emission pathway scenario (SSP 2.6), the intermediate emission scenario (SSP 4.5), and the worst emission scenario (SSP 8.5) developed by the Canadian Earth System Model (CanESM5) (Swart *et al*., 2019) and the Beijing Climate Center Climate System Model (BCC-CSM5) (Zhou *et al*., 2014). These layers were extracted, clipped, and converted to ASCII format using ArcGIS 10.7 to calculate the habitat suitability of *C. simensis*.

Topographic attributes such as altitude, slope, and aspect were extracted from the 90 m resolution STRM DEM (Jarvis *et al*., 2008). The slope categories were flat (0–3%), gently sloping (3–8%), sloping (8–15%), moderately sloping (15–30), steep (30–50%), and very steep (>50%) (Belete Berhanu *et al*., 2013). The ecoregion layer was obtained from Olson *et al*. (2001). The soil layer was extracted from FAO/UNESCO (2003). The global land cover map was obtained from the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/). All of the data was processed using ArcGIS 10.7's spatial analyst tool before being used as input data for the MaxEnt. We also resampled all other topographic predictor variables based on the bioclimate data resolutions. To minimize the prediction uncertainty and increase the precision of the prediction, we used average prediction values for the species' predictions of suitability and distribution. We divided the average of two general circulation models into six categories: 2050/70_2.6, 2050/70_4.5, and 2050/70_8.5 (Table 2). In addition, we also averaged the overall scenarios for 2050 and 2070 (Table 2).

Before running the model, the statistical R-software version 4.1.2 was used to perform a correlation test to remove one of the correlated variables with a percent of coefficients of r>0.80 (Zhao *et al*., 2019). We computed the multi-collinearity using the Variable Inflation Factors (VIF) threshold, and then we retained a total of ten variables using VIF<10 values (Table 1).

Table 1. A list of bioclimatic variables used to model climatically suitable habitats and distribution of *C. simensis* across the Ethiopian highlands.

Category	Environmental variables description	Abbreviation	Unit	VIF*	Source	Contribution (%)
Bioclimatic	Isothermality (Bio2/Bio7(*100)	Bio3	%	3.7	https://www.worldclim.org/data/index.html	0.2
	Max temperature of warmest month	Bio5	°C	9.9		65.4
	Precipitation of driest month	Bio14	mm	7.6		0.8
	Precipitation of coldest quarter	Bio19	mm	1.6		0.3
Topographic attribute	Altitude	Alt	meter	2.2	https://lpdaacsvc.cr.usgs.gov/appeears	1.6
	Ecoregion	Ecorg	unitless	2.4		16.1
	Soil	Soil	unitless	7.3		10.4
	Vegetation	Vegt	unitless	1.4		3.6
	Slope	Slope	unitless	1.4		1.6
	Aspect	Asp	0degree	1.2		0.1

*Variable inflation factors

MaxEnt model setting

The maximum entropy algorithm (MaxEnt, Phillips *et al*., 2006) is suitable for presence-only data (Elith *et al*., 2006; Bean *et al*., 2012; Phillips *et al*., 2017; Morales *et al*., 2017). This modeling approach shows better model accuracy (Elith *et al*., 2006), transferability (Tuanmu *et al*., 2011), and reliability even for small sample sizes (Pearson *et al*., 2007). Out of the total data points used, 70% of the distribution points were randomly selected as training data to build a model and the remaining 30% as test data for model verification (Elith *et al*., 2006). We used MaxEnt's software default parameters (Phillips *et al*., 2006), in addition to the following settings: replicated 10 times, replicated run type "subsample," and maximum iterations of 5,000. Ten thousand background points were randomly generated from the entire study area. During the model's run, we also adjust the predictor variables as continuous (climate variables, altitude, and aspects) and categorical (ecoregion, soil, slope, and vegetation).

Model validation and accuracy

We measured the accuracy of the MaxEnt models using the area under the receiver operating characteristics curve (AUC), which is a threshold-independent measure used to discriminate between the pseudo-absence and presence of data (Fielding and Bell, 1997; Guisan and Zimmermann, 2000). Its accuracy value ranges from 0 (random discrimination) to 1 (perfect discrimination) (Hosni *et al*., 2020). The response curve for each bioclimatic variable was used to estimate the relationship between habitat suitability for the target/study species. The curves show how the predicted probability of presence changes as each environmental variable is varied, keeping all other environmental variables at their average sample value. We also used a 10-percentile training presence logistic threshold to estimate habitat suitability and unsuitability for a target species in each scenario and evaluated the jackknife test to determine the individual predictor variables (Phillips *et al*., 2006).

The Maxent outputs were further processed using ArcGIS 10.7 and the habitat suitability scores were divided into three categories: unsuitable, moderately suitable, and highly suitable (Boitani *et al*., 2008). Subsequently, under the SSP 2.6, SSP 4.5, and SSP 8.5 scenarios developed by two general circulation models (GCMs) or global climate modeling systems. The changes in the expected habitat distribution and future predictions of *C. simensis* were measured. The areas of loss, gain, and stability was computed by subtracting future and current habitat suitability models.

RESULTS

Evaluations of the model and its importance to variables under current climatic condition

The area the under-curve value of the receiver operating characteristic (ROC curve) for the *C. simensis* habitat suitability index shows an average test AUC of 0.969 + 0.016 (Mean + SD) for the 10 replicate runs. This AUC score indicates an excellent ability of the model to discriminate between suitable and unsuitable habitats of the species. The performance of a model confirms that the selected predictor variable provides a reasonable prediction of the distribution of this endemic and endangered species.

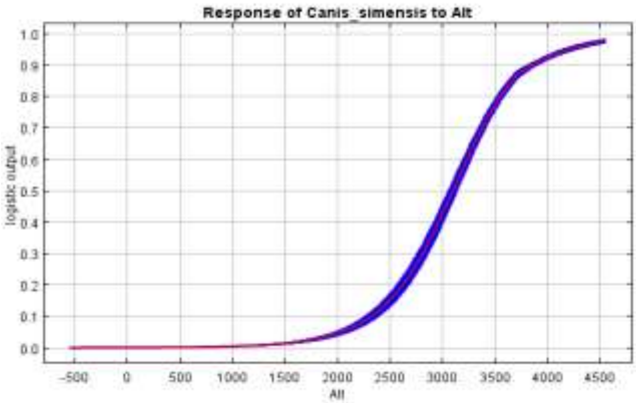
Amongst the ten ecological input variables, *C. simensis*'s current distribution was significantly influenced by the maximum temperature of the warmest month and the ecoregion that contributed 65.4% and 16.1%, respectively (Table 1). The precipitation of the driest month and the precipitation of the coldest quarter had the lowest contributions to the model (Table 1).

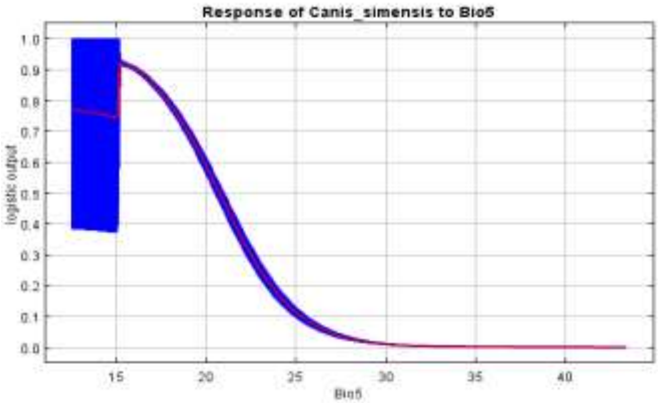
Predicted current and potential distribution and habitat suitability model of *C. simensis*

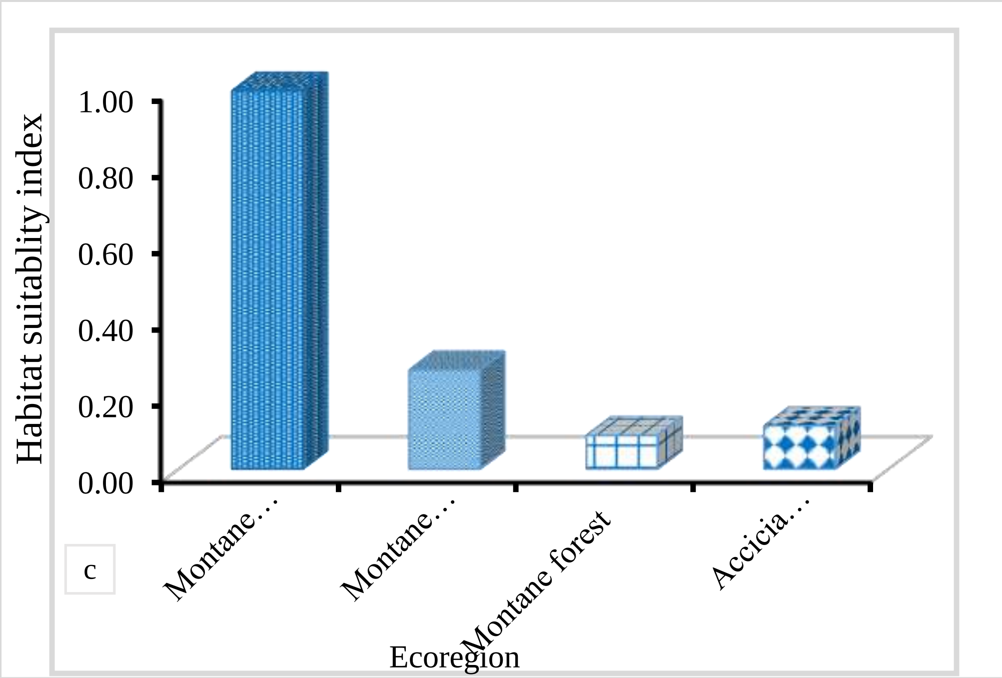
The response curves indicate how each predictor variable affects the MaxEnt prediction (Fig. 2). The curve also shows how the predicted frequency of presence changes as each predictor variable is changed, while the other predictor variables remain at their average value. Results revealed that habitat suitability increased with increasing altitude (Fig. 2a), whereas the maximum temperature of the warmest month had the reversal effect (Fig. 2b). Furthermore, the ecoregion, particularly the montane moorland, montane grassland, and wood land was observed to influence the distribution (Fig. 2c). The habitat suitability index of Ethiopian wolf was highly influenced by the steeply slope category (Fig. 2d). Vegetation types such as broadleaved evergreen and shrubland deciduous forest had significant impacts on the distribution of the species (Fig. 2e).

Under the current climate change combined with other ecological predictors, the predicted suitable area for the wolf was 2,779,658 hectares. The total suitable area was further classified as highly suitable with an area of 346,454.1 (12.46%) hectares whereas 2,433,203.982 (87.53%) of the remaining area was moderately suitable (Fig. 5). These total suitable areas are too small compared to the total areas of Ethiopia. Predicted model output shows that only Ethiopian highland areas have suitable habitats, particularly

Bale and Simen Mountains National parks. Overall, results confirm that *C. simensis* habitats have been fragmented throughout the Ethiopian highlands, particularly in national protected areas such as Bale Mountains National Park, Arsi Mountains, Simen Mountains National Park, northern Shewa, southern Wollo, and northern Wollo.



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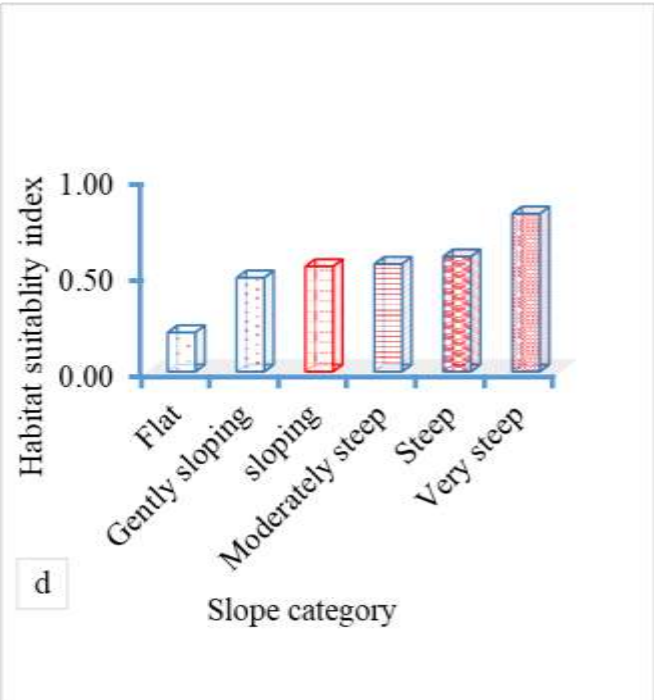
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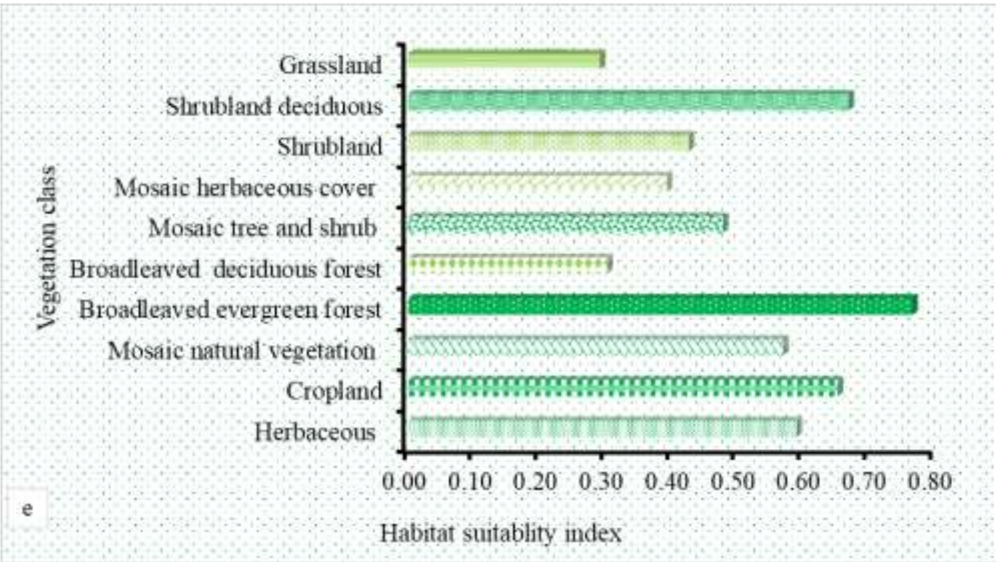

Fig. 2. The most important environmental predictor variables influencing the distribution and suitability of *C. simensis* are: (A) altitude (Alt), (B) maximum temperature of the warmest month (Bio5), (C) ecoregion, (D) slope category, and (E) vegetation class.

Model evaluations and significant variables for *C. simensis* habitat distribution under different future climate scenarios

All projected output values under the various future climate change scenarios indicated that the AUC ranged between 0.978 and 0.985. The overall average of the two general circulation models was comparable at AUC values of 0.980 and 0.982 in 2050 and 2070, respectively. The jackknife test revealed that the habitat suitability and distribution of a target species were mainly influenced by the maximum temperature of the warmest month, altitude, and ecoregion (Fig. 3a-c). There was a similar percent contribution in both global climates modeling systems, ranging between BCC-SCM (96.7–96.8) and CanESM (95.5–95.8) under all future climate scenarios. Other predictor variables showed variation in percent contributions and jackknife tests under different scenarios (Fig. 4).

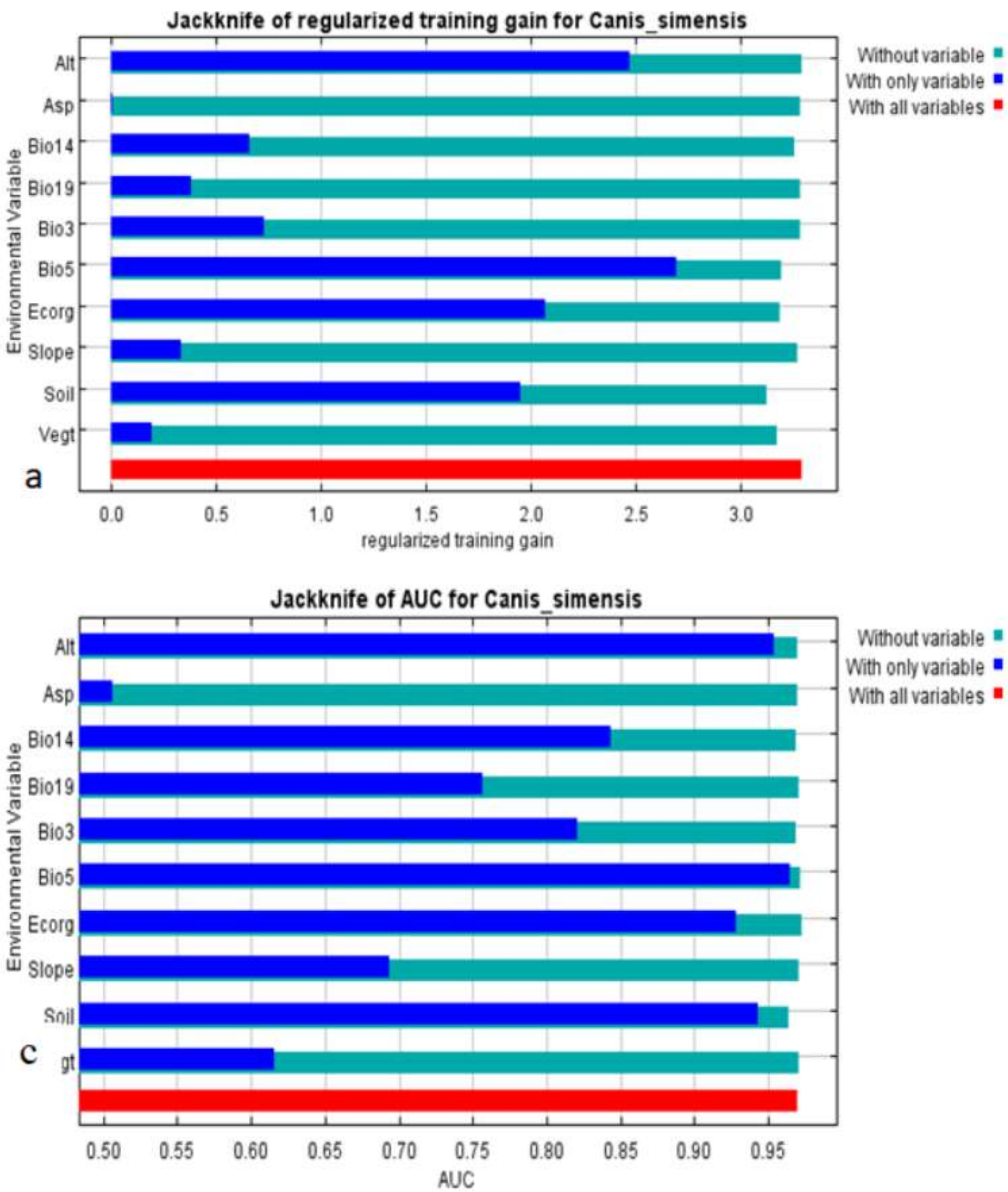

Fig. 2. The most important predictor variables identified by jackknife analyses.

Predicted distribution of *C. simensis*

The projected habitat suitability model under the future climate change scenarios developed by BCC-CSM5 and CanESM shows climate change would significantly affect the target species distribution (Fig. 5). These impacts were not uniform throughout the Ethiopian highlands in both the BCC-CSM5 and CanESM model systems. The highest gain in the suitable habitat of *C. simensis* was predicted under individual scenarios SSP 2.6 (152.84%) and 4.5 (105.91%) for the year 2050 under BCC-CSM5, as well as SSP 2.6 (172.19%) and 8.5 (157.88%) for the years 2050 and 2070, respectively, under CanESM. Furthermore, the highly suitable areas also showed a moderate gain in both global circulation models, such as BCC-CSM SSP 2050 2.6 (87.90%), BCC-CSM SSP 2070 4.5 (86.18%), and CanESM SSP 2050 2.6 (90.29%) and CanESM SSP 2050 8.5 (94.69%).

We have also evaluated the highest gain in suitable predicted habitat for *C. simensis* by averaging under 2050 at 2.6 (162.5%) and 4.5 (126.5%) (Table 2). In addition, the overall average suitable predicted habitat for C. *simensis* in the 2050s and 2070s was 131.3% and 112.6% of suitable habitat gained, respectively (Fig. 5; Table 2). Overall, model projections under future emission scenarios showed a highly suitable trend, exclusively restricted towards higher altitudes in the Ethiopian mountains (Fig. 5). There were also other fragmented suitable habitat areas newly located in the Ahmar Mountains, Eastern Ethiopian Highlands, Sidama, Gamo, Kefa, Guraghe, western Shewa, Addis Ababa areas, eastern Gojam, central Gondar, southern Gondar, western Gondar, and Eastern Tigray (Fig. 5).

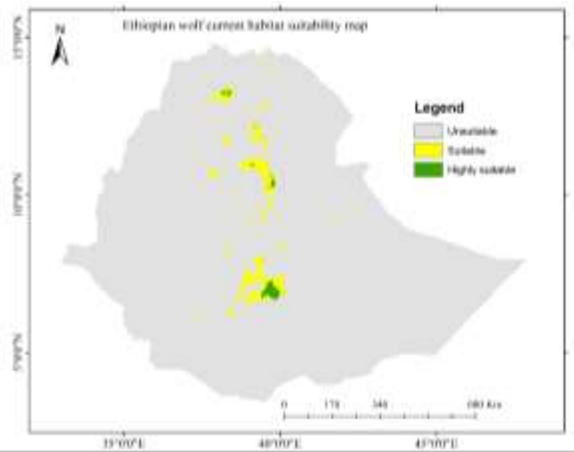

Fig. 4. Current predicted habitats of the Ethiopian wolf, grey (unsuitable), yellow (suitable), and green (highly suitable).

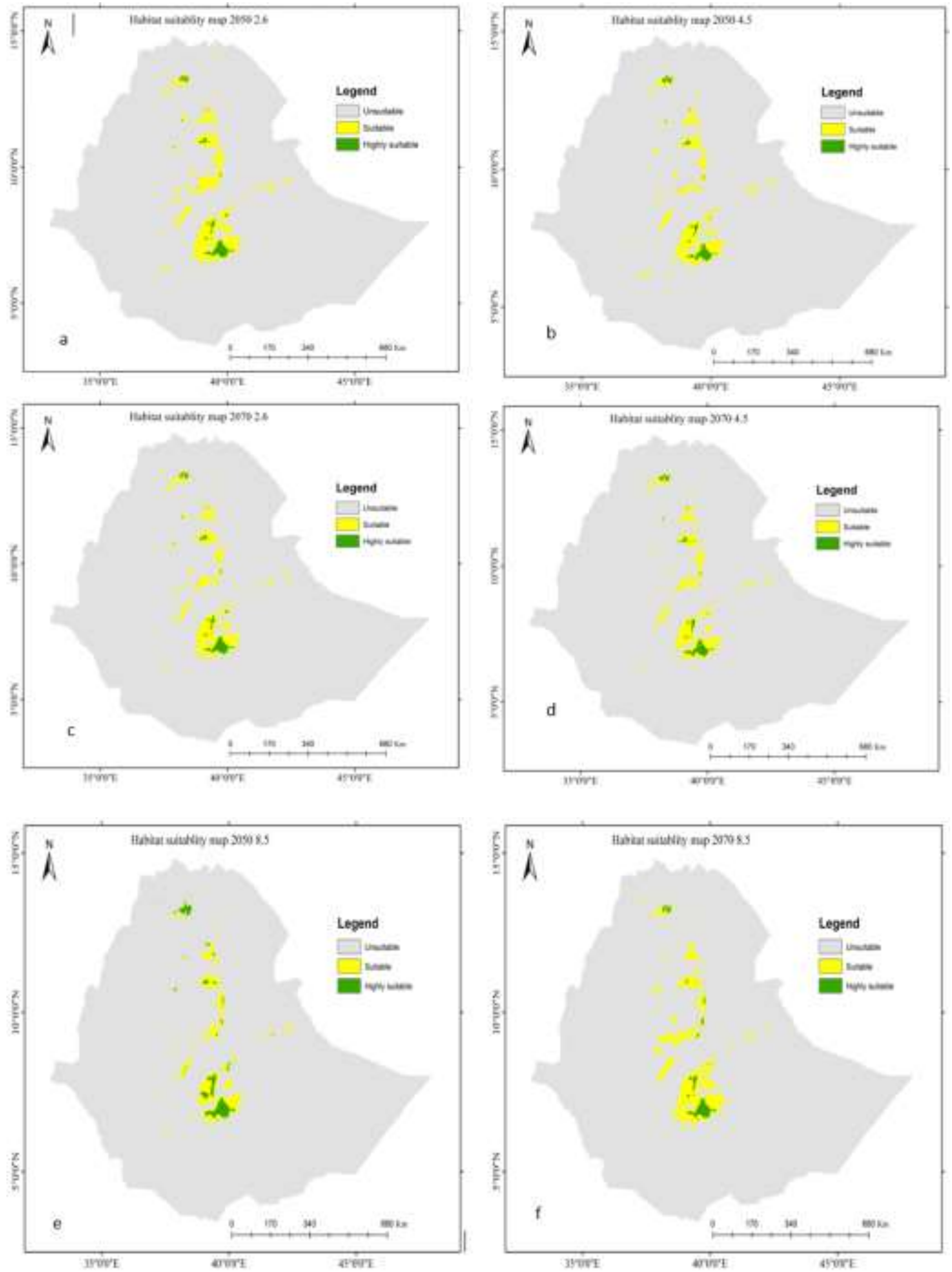

Fig. 5. The average predicted change in the habitat distribution of *C. simensis* in the Ethiopian highlands.

Table 2. Predicted average change in suitable habitats of Ethiopian wolf (*C. simiensis*) under two general circulation models.

		Highly suitable (ha)						**Suitable (ha)**					
Scenarios	**Total suitable (ha)**	**Stable**	**%**	**Gain**	**%**	**Loss**	**%**	**Stable**	**%**	**Gain**	**%**	**Loss**	**%**
		346,454						**2433204**					
2050 2.6	267,088.0	308,679.8	89.1	193,671.2	55.9	62,277.8	18.0	1,213,372.0	49.9	395,4356.0	162.5	377,156.2	15.5
2050 4.5	4,670,091.0	298,270.4	86.1	174,367.6	50.3	72,687.2	21.0	1,125,069.0	46.2	3072,384.5	126.3	465,459.4	19.1
2050 8.5	4,148,806.0	305,894.9	88.3	298,681.6	86.2	65,062.7	18.8	989,991.0	40.7	2554,239.0	105.0	600,537.4	24.7
Average	302,8661.7	304,281.7	87.8	222,240.1	64.1	66,675.9	19.2	1,109,477.3	45.6	3193,659.8	131.2	481,051.0	19.8
2070 2.6	487,4590.0	295,383.8	85.3	189,778.4	54.8	75,573.7	21.8	1,056,276.0	43.4	2512,342.0	103.3	534,252.3	22.0
2070 4.5	4324788.0	300,284.5	86.7	166,010.2	47.9	70,673.1	20.4	1,10,7745.5	45.5	2750,748.0	113.1	482,782.6	19.8
2070 8.5	546,8161.5	297,951.4	86.0	176,628.6	51.0	73,006.2	21.1	1,109,543.5	45.6	2958,527.0	121.6	480,984.8	19.8
Average	385,987.8	297,873.2	86.0	177,472.4	51.2	73,084.3	21.1	1,091,188.3	44.8	2740,539.0	112.6	499,339.9	20.5

DISCUSSION

SDMs are used to generate habitat suitability maps, which are vital to designing and developing biodiversity conservation priority areas to effectively conserve all species (Di Pasquale *et al*., 2020; Rather *et al*., 2020). This study investigated both current and future potentially suitable habitats for *C. simensis* across the Ethiopian highlands, with a focus on the impacts of topographic, landscape attributes, and climate change on its habitat using the MaxEnt model. The results indicate that the suitable habitats of the species were predicted with a high degree of accuracy, with an AUC of 0.969 and a standard deviation of 0.016. The current results were comparable to those predicted for grey wolves (*Canis lupus*) and Ethiopian wolf (*C. simensis*), with AUC values of 0.971 (Kabir *et al*., 2017) and 0.98 (Yericho Berhanu *et al*., 2022), respectively. Evangelista *et al*. (2008) predicted an AUC value of 0.89 for *Tragelaphus buxtoni* in Bale Mountain, 0.902 for *Capra walia* in Ethiopia's Simien Mountains (Berihun Gebremedhin *et al*., 2021), and 0.913 for golden jackal in northeastern Italy (Torretta *et al*., 2020). These figures indicated good accuracy in evaluating the success of an ecological niche model (Swets, 1988; Elith *et al*., 2011).

Our findings showed among the ten predictor variables retained for modeling, the maximum temperature of the warmest month, the ecoregion, soil, and vegetation mostly affected the predicted suitable habitats of *C. simensis*. Similarly, ecological niche model prediction confirms that the highest temperature in the warmest month is the most influential predictor of Canidae species distributions (Porto *et al*., 2021). Evidence shows that temperature is one of the most important predictors of future range expansion for species (Smeraldo *et al*., 2021). The suitability of *C. lupus*, on the other hand, was influenced by the distances to the river and road, the mean temperature of the wettest quarter, and the distance to the river, which contributed the most to the model, while soil, altitude, and annual precipitation contributed the least (Kabir *et al*., 2017). A recent study conducted on the *C. simensis* habitat suitability showed that annual mean temperature highly influenced its habitat suitability (Yericho Berhanu *et al*., 2022). Temperature and precipitation patterns, from monthly to seasonal, have a direct impact on species' biological behavior and physiology, as well as distribution, abundance, and interactions (Hirzel and Le Lay, 2008; Walther *et al*., 2002). These variations in the contributions of bioclimatic variables on species distribution in different regions could be explained by the influence of agroecological variety around the world (Chala Adugna *et* *al*., 2022). Habitat fragmentation had a significant impact on predicted habitat suitability and the distribution of wildlife (Guisan and Zimmermann, 2000). Similar to this study, climate change and anthropogenic activities have a major impact on the expected distribution, habitat connectivity, and genetic diversity of an endangered species (Zhao *et al*., 2019).

The present result showed that montane moorland had the highest HSI. The Afro-alpine habitats, mainly in subalpine moorland, are highly suitable habitats for the flag species of the Ethiopian wolf (*C. smensis)* (Randall *et al*., 2006: Tallents, 2007). Similarly, alpine vegetation has been found to provide a better suitable habitat for Ethiopian wolf (Marino, 2003a). It is associated with the availability of foraging resources such as three species of rodent endemic to the southern highlands of Ethiopia: two murine rats, Arv*icanthis blicki* and *Lophuromys melanonyx*, and the *Rhizomyid* giant mole rat, *Tachyoryctes* macrocephalus (Tallents, 2007). The broad evergreen (0.77 HSI), shrubland deciduous (0.67 HSI), and cropland (0.65 HSI) are also the most influential predictor variables for the predicted habitat suitability of *C. simensis*. Broadleaf and conifer forest have a significant impact on the distribution and habitat suitability of other Canidae species, such as the endangered *Cuon alpinus* (Thinley *et al*., 2021). The most significant and effective indicators of the presence and distribution of golden jackals (*Canis aureus*) were broadleaf woods and shrublands (Torretta *et al*., 2020). Grasslands and deciduous woodlands significantly influence *Cuon alpinus* distribution and adaptability (Jenks *et al*., 2012). The vegetation integrated with density estimates of prey species' habitat connections has a significant impact on ecological niches (Tallents, 2007). Among the slope categories, moderately steep, steep, and very steep boosted habitat suitability for a targeted species. For an endangered Canidae (*Cuon alpinus*) the distribution and suitability are more highly influenced by slope than the other environmental predictors (Thinley *et al*., 2021). According to Kabir *et al*. (2017), areas free of human disturbances and narrow valleys were the most highly suitable for *C. lupus*, whereas habitat in lower altitude areas with more human access was less suitable. *C. simensis* uses all Afroalpine habitats; they prefer open areas with short herbaceous and grassland ecosystems where rodents are most plentiful, as well as flat or gently sloping slopes with deep soils and poor drainage locations (Marino and Sillero-Zubiri, 2013). Like the Ethiopian wolf, the other flag species, the *Walia ibex*, has mainly utilized the steepest slopes as highly suitable areas (Berihun Gebremedhin *et al*., 2021).

Results indicated that highly suitable habitats are very small, fragmented, and restricted to the isolated Afromontane Ethiopian highlands. New fragmented and very small suitable habitats were predicted in the present study, such as the Ahmar Mountains in eastern Ethiopia (Hararghe), Addis Ababa areas, and the central Ethiopian highlands. However, relative to the entire area of the country, the overall predicted suitable habitat for *C. simensis* is very low. The future climate change in both global circulation models had a significant change in the predicted suitable habitat of the study species. The averaged model predictions for the species' suitable habitat show that under the 2050 and 2070 future scenarios, respectively, 131.3% and 112.6% of the species' suitable habitat were gained. However, averaged out, 24.7 percent and 22% of the area were lost under the 2050_8.5 and 2070_2.6 scenarios, respectively. Overall, 19.8% and 20.5% of the suitable areas were lost under the 2050 and 2070 scenarios, respectively. However, in contrast to our study, similar studies indicate that over the next couple of decades of climate change, there is expected to be a total loss of the potentially suitable habitat distributions of the Ethiopian wolf (*C. simensis)* (Yericho Berhanu *et al*., 2022). Predictions indicate that the distributions of Canidae species, such as the African wild dog (*Lycaon pictus*), have collapsed under worst-case scenarios (Rabaiotti, 2019). Although they are unrelated species, *C. simensis* has very limited predicted suitable areas, as do the endemic mammals Theropithecus *gelada* (Ahmed Seid *et al*., 2023) and *Capra walia* (Berihun Gebremedhin *et al*., 2021). This study shows climate change poses an unprecedented threat to global biodiversity by disrupting habitat distribution patterns (Sales *et al*., 2020). Historically, Ethiopian Wolf were found in eastern and southern Ethiopia (Hararghe and Sidamo) regions, but now they are locally extinct (Yalden, 1983; Marino, 2003b). This might be due to climate change and anthropogenic pressures or shifting in the geographic range. New strategies are needed to avert the biodiversity loss resulting from the effects of climate change across the globe (Lu *et al*., 2020); otherwise, such shifting and changes may lead to the local extinction of a species (Preau *et al*., 2020).

Continuous climate change has a significant detrimental effect on the geographic range of this species notably under all-future climate change scenarios. Eastern Ethiopian highlands, the Southeastern regions, central Ethiopia, the northwestern region, and Eastern Tigray all have newly occupied and extremely fragmented suitable habitats. These areas are vulnerable to further fragmentation, deforestation, grazing, and increased human settlements (Chala Adugna *et al*., 2022). It is clear that, as a result of climate change, species' geographic distributions may be extended, altered, or shifted in the future (Sales *et al*., 2020). The animal populations lose a substantial portion of their habitats as a result of changing climate conditions, particularly in the Himalayan and Hindu Kush regions (Ali *et al*., 2021).

Though sympatric African wolves have widely adapted environments (Macdonald *et al*., 2019; Tariku Mekonnen e*t al*., 2019), the EWs have been limited to the Ethiopian highlands. It's important to note that anthropogenic activity expansions in the Ethiopian wolf's habitat are likely attracting African wolves, providing the species with an impact area for inferred competition (Tariku Mekonnen *et al*., 2019). Understanding the effects of future climate change on species distribution would aid in the development of conservation policies aimed at reducing the danger of future biodiversity loss (Garcia *et al*., 2014; Kujala *et al*., 2013; Nazeri *et al*., 2014; Shrestha and Bawa, 2014; Aryal *et al*., 2016).

Overall, identifying data on a targeted species' geographical range of highly suitable habitat is critical for laying the plans for conservation efforts and formulating policies (Thorn *et al*., 2009; Aryal *et al*., 2016). In this study, the change in the location of suitable habitats due to the warming climate over time may lead to a decrease in connectivity, resulting in the local extinction of species (Preau *et al*., 2018). The wolf population is positively related to diurnal rodent density, and rodents account for 79.5% of wolf prey in the Afroalpine (Mesele Yihune and Afework Bekele, 2014). Effective conservation of a taxon should have included not only wolves but also their prey. This habitat suitability model helps with future conservation plans for endangered and declining species. However, it needs more data on the areas inhabited by a species within its range across fragmented patches which the target species inhabited (Boitani *et al*., 2008). As an example of conservation success, the populations of Walia ibex (*Capra walie*) have recently increased due to the conservation of Simien Mountain National Park through effective collaboration between Regional and Federal responsible sectors (Mengistu Wale, 2016).

CONCLUSION

More accurate prediction models of species distribution and habitat suitability have made a substantial contribution to helping ecologists get a better grasp of improved ecological evidence. The MaxEnt model has great prediction power in distinguishing between *C. simensis*' potential suitable and unsuitable habitats. Our research successfully predicted habitat suitability under present and future climate change scenarios. The results indicate that the maximum temperature of the warmest month, ecoregion (specifically montane moorland and montane grassland and wood land), soil and vegetation (broadleaved evergreen and shrubland deciduous) and slopes (steep and very steep) were the most important bioclimatic variables for the prediction of suitable habitats and their distribution. Predicted results showed that the species has a small fragmented suitable habitat, which shifted through time. To conserve and manage the endemic and endangered *C. simensis* across the Ethiopian highlands, conservation efforts such as habitat protection or restocking of fragmented forests, assessment of conservation challenges, and reducing global climate change causes are needed. Further exploration of the ecological niches of the species associated with its prey range overlap is needed to better understand the possible effects of biotic factors on Ethiopian wolf habitat suitability and distribution.

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