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## Journal of Threatened Taxa

Building evidence for conservation globally

[www.threatenedtaxa.org](http://www.threatenedtaxa.org)

ISSN 0974-7907 (Online) | ISSN 0974-7893 (Print)

### COMMUNICATION

#### ECOLOGICAL NICHE MODELLING PREDICTS SIGNIFICANT IMPACTS OF FUTURE CLIMATE CHANGE ON TWO ENDEMIC RODENTS IN EASTERN AFRICA

Aditya Srinivasulu, Alembrhan Assefa & Chelmala Srinivasulu

26 April 2021 | Vol. 13 | No. 5 | Pages: 18164–18176

DOI: [10.11609/jott.6715.13.5.18164-18176](https://doi.org/10.11609/jott.6715.13.5.18164-18176)



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## Ecological niche modelling predicts significant impacts of future climate change on two endemic rodents in eastern Africa

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**Abstract:** The impact of climate change on rodents is well studied, however, many of these studies are restricted to the Americas. Small- to medium-sized rodents, especially murids, are restricted in their home range and microclimatic niche breadth, and are known to be more sensitive to changes in bioclimatic conditions over time. We analyzed the effect of future climatic scenarios in the near and distant future, using two global climate models (CanESM5 and MIROC-ES2L) for two shared socio-economic pathways (SSP2-4.5 and SSP5-8.5), on two eastern Africa endemic small-bodied mice: *Stenocephalemys albipes* and *Mastomys awashensis*. Our results indicate that while *S. albipes* showed increases in area of climatic suitability in the future, *M. awashensis* is predicted to suffer severe decline in the area of its fundamental niche.

**Keywords:** Awash Multimammate Mouse, Ethiopian White-footed Mouse, decline, microclimate, MaxEnt.

**Editor:** Anonymity requested.

**Date of publication:** 26 April 2021 (online & print)

**Citation:** Srinivasulu, A., A. Assefa & C. Srinivasulu (2021). Ecological niche modelling predicts significant impacts of future climate change on two endemic rodents in eastern Africa. *Journal of Threatened Taxa* 13(5): 18164–18176. <https://doi.org/10.11609/jott.6715.13.5.18164-18176>

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**Funding:** The major funding for carrying out this research was granted by the Government of Ethiopia and Adigrat University, Ethiopia.

**Competing interests:** The authors declare no competing interests.

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**Author contribution:** All authors contributed equally to the study, analysis, and writing the manuscript.

**Acknowledgements:** We thank the head, Department of Zoology, Osmania University, India and head, Department of Biology, Adigrat University, Ethiopia for the facilities, and the Ethiopian Government for Research Fellowship to AA.



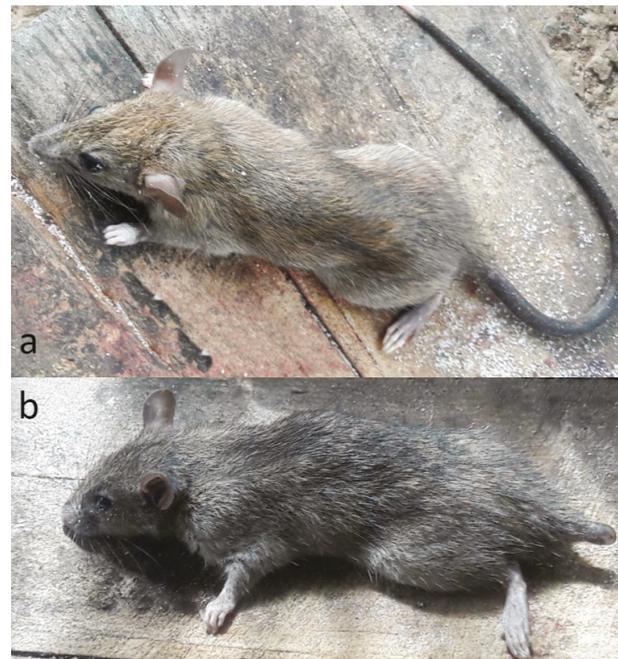


## INTRODUCTION

Rodents are the most diverse and abundant groups of mammals, accounting for approximately 2,200 species (Monadjem et al. 2015), distributed across the world on every continent except Antarctica (Nowak 1999). They occur in a wide range of terrestrial habitats, and serve the purpose of ecosystem engineers (Zhang et al. 2003) and keystone species in an ecosystem. Africa supports a large diversity of rodent species, with at least 463 known species (Monadjem et al. 2015), and new species described regularly; however, the ranges and habitats of some rodent species in Africa are not clearly known, due to many reasons ranging from inaccessible localities to insufficient data or resources (Kingdon 1997; Habtamu & Bekele 2008; Takele et al. 2011). This is of especial concern as rodents are not only diverse, but are an integral part of the ecosystem's functioning and health, contributing essential services (Fischer 2017). They are also of biogeographic, systematic, and conservation interest and priority (Happold 2013; Monadjem et al. 2015).

Rodents distributed in xerothermic habitats have been known to benefit from climate change towards a warmer, drier climate scenario, most likely due to their thermo-xerophilia being supported by the climatic conditions (Cameron & Scheel 2001). Climate change towards warmer and drier conditions has also resulted in an increase in species diversity in rodents in warm regions (Szpunar 2008). It is also possible that due to the effect of changing climate scenarios, migrations and emigrations take place, resulting in new regional populations being seeded and established in order to occupy the fundamental niche (Royer et al. 2016). As an extension of the conclusions drawn by Millien & Damuth (2004), treating fragmented populations as islands, it may be inferred that there is a possible slowing of the evolutionary rate of rodents as a result of climate change.

Hutchinson (1957) proposed the concept of the 'ecological niche' – an abstract representation of the biotic and abiotic factors deciding and limiting the distribution and abundance of a species. Identifying the ideal environmental niche of a species by accounting for certain limiting factors is one of the aims of ecological niche modelling (ENM) – this ideal niche is referred to as the fundamental niche (Griesemer 1994). The fundamental niche does not represent the real distribution of the species; in fact, it is usually larger than the realised distribution of the species (Soberón & Arroyo-Peña 2017). Ecological niche modelling uses



**Image 1. a.—Ethiopian White-footed Mouse *Stenocephalemys albipes* (Rüppell, 1842) | b—Awash Multimammate Mouse *Mastomys awashensis* (Lavrenchenko et al. 1998). © Alembrhan Assefa.**

presence-only or presence-absence occurrence data of a species and analyses it against a set of spatial covariates—most often, bioclimatic variables are used as the covariates in a climate change ENM study. Many diverse algorithms may be used for ENM, including generalised linear models (GLM), multivariate adaptive regression splines (MARS), and random forests (RF). MaxEnt (Phillips et al. 2006), however, is by far the most widely used algorithm due to its use of presence-only data, ease of access, customizability, and robustness (Ortega-Huerta & Peterson 2008; Elith et al. 2011; Merow et al. 2013; Radosavljevic & Anderson 2014).

The present study analyses the effect of current and future climate scenarios on the predicted fundamental niche of two Ethiopian-endemic rodents, the Awash Multimammate Mouse *Mastomys awashensis* (Lavrenchenko et al. 1998) and the Ethiopian White-footed Mouse *Stenocephalemys albipes* (Rüppell, 1842) (Image 1). It aims to predict the impact of future climate change pathways (SSP2-4.5 and SSP5-8.5) on the niches of these species using maximum entropy (MaxEnt) modelling.

## MATERIALS AND METHODS

### Study area

This study is based in Ethiopia and Eritrea, as both *Mastomys awashensis* and *Stenocephalemys albipes* are endemic to this region (Image 2). *M. awashensis* is distributed in the scrublands of the Awash River bank, which primarily comprises small Acacia and Commiphora trees and thorny scrubs, and is also found in agricultural fields and wild areas of the northern highlands (Lavrenchenko et al. 1998; Meheretu et al. 2014). *S. albipes* occur in moist montane forests, scrublands at high altitudes, and agricultural fields (Yalden & Largen 1992; Tilaye 2005; Kassa & Bekele 2008) (Image 2). The study region varies widely in altitude, geography, and climatic conditions, resulting in a high diversity of biological resources and high levels of endemism. The altitude of the region varies from 115m below sea level to 4,620m above sea level, and it can be classified into three climatic zones – tropical, subtropical, and cool. The mean annual temperature ranges 16–27 °C, and the

annual precipitation ranges 510–1,280 mm. While the study is restricted to Ethiopia and Eritrea, the ecological niche modelling (ENM) was conducted on the entirety of continental Africa to account for ecological niche data outside the political borders of these countries; final models were then cropped to Ethiopia and Eritrea’s national boundaries.

### Data collection

Occurrence data of the two study species were collected from Ethiopia and border regions in Eritrea. A total of 101 presence records were collected (34 for *M. awashensis* and 67 for *S. albipes*) from published literature (Lavrenchenko et al. 1998; Habtamu & Bekele 2008; Colangelo et al. 2010; Assefa & Srinivasulu 2019) and from GBIF (accessed August 2020) (Image 2; Appendix 1). Occurrence data of each species were spatially thinned using the package spThin (Aiello-Lammens et al. 2015) in R such that points within a 2km<sup>2</sup> area of each other were treated as duplicates and removed to account for spatial bias and autocorrelation

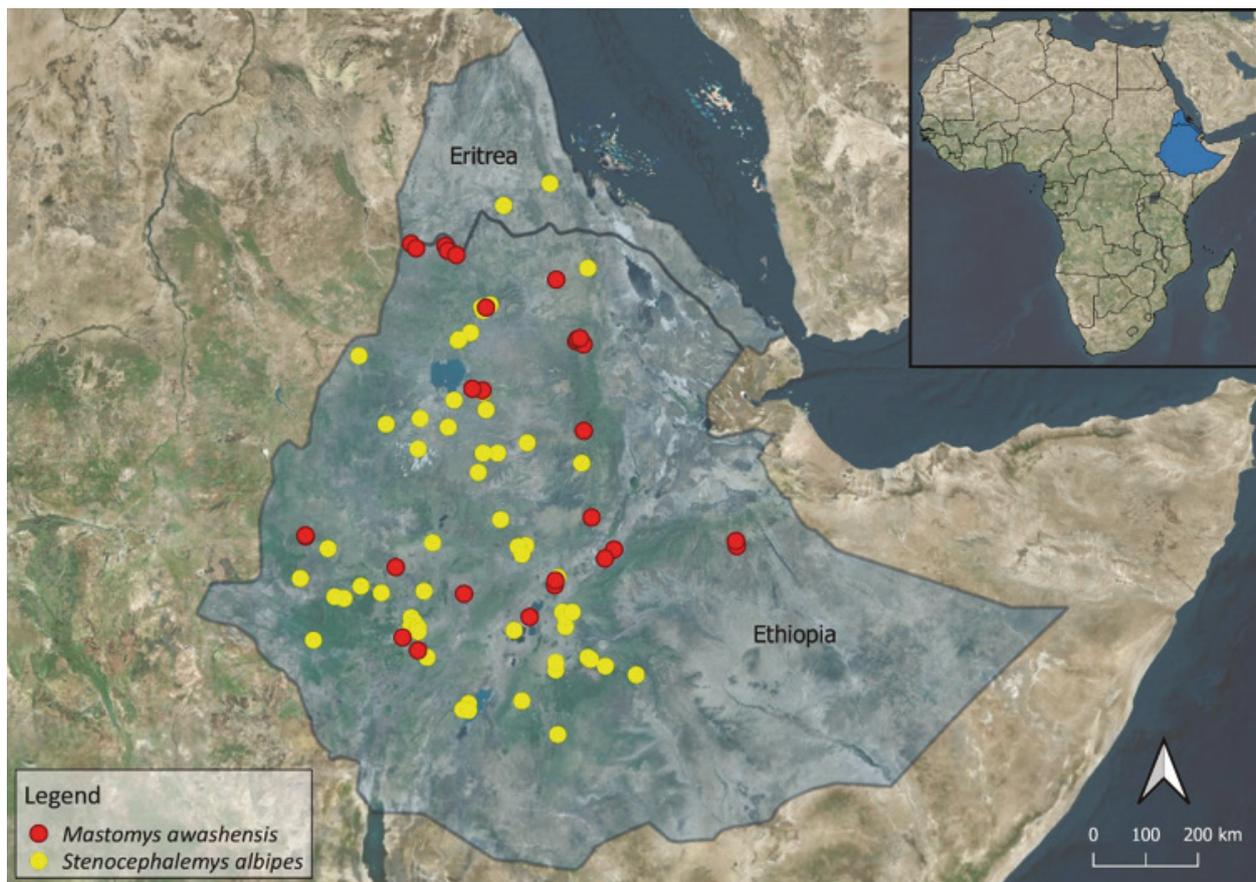


Image 2. Satellite map of the study area, with occurrence localities (before spatial rarefaction) shown (inset – satellite map of continental Africa, with study area highlighted in blue).



in sample collection.

Nineteen bioclimatic environmental variables were acquired at a resolution of 2.5 arc-minutes from the Worldclim 2 database for the current time period (Fick & Hijmans 2017). For future scenarios, 2.5 arc-minute resolution data from the Coupled Model Intercomparison Project 6 (CMIP6) were acquired for two shared socioeconomic pathways - SSP2 representing a middle-of-the-road scenario (Fricko et al. 2017) and SSP5 representing fossil-fuelled development in the future (Kriegler et al. 2017). Two global climate models were used to account for inter-model disparities in projection (Porfirio et al. 2014) - MIROC-ES2L (Tachiiri et al. 2019a,b) and CanESM5 (Swart et al. 2019a,b). Data were acquired for the 2041–2060 (near future) and 2061–2080 (distant future) time periods.

An analysis of multicollinearity conducted using the package *Virtualspecies* (Leroy et al. 2015) in R version 4.0.2 (R Core Team 2020) was used to select relatively uncorrelated variables for the modelling. Variables with an absolute value of Pearson's  $r > 0.75$  were subjected to pairwise comparisons of perceived ecological importance based on our understanding of the ecology and biology of the two species. All climate data were initially cropped to the extent of continental Africa; islands surrounding Africa including Madagascar were included, but southern Europe, the Middle East, and the Arabian Peninsula were not used.

### Ecological niche modelling

A presence-only approach was used to model species distributions, using MaxEnt version 3.4.1 (Phillips et al. 2006); however, careful consideration of biases and selection of parameters is an essential step in order to maximise the robustness and reliability of niche models generated using MaxEnt (Derville et al. 2018). Hence, parameterisation was done according to the processes outlined in Merow et al. (2013) and Feng et al. (2019). To account for spatial bias, a Gaussian kernel density bias file of bandwidth 0.5 was created using the package *SpatialEco* (Evans 2020) in R, in order to weight the generation of background (pseudo absence) points for the analysis.

The model was parameterised for feature classes and regularisation multipliers using the package *ENMEval* (Muscarella et al. 2014). We tested a set of five regularisation multipliers: 0.5, 1, 2, 3, and 5, and six feature classes: Linear, Linear+Quadratic, Hinge, Hinge+Quadratic, Linear+Quadratic+Product, and Hinge+Quadratic+Product. Five-fold cross-validation was used and model performance was assessed using

the area under the receiver operating characteristic curve (AUC) and the true skill statistic (TSS).

The continuous models for each scenario and each time period, as output by MaxEnt, were reclassified according to the maximum test sensitivity+specificity (MSS) threshold into binary models – the positive cells represented the fundamental niche of the species for each scenario and time period according to bioclimatic data. Finally, the binary models were cropped to Ethiopia and Eritrea's national boundaries. Area of climatic suitability was calculated as a percentage based on the ratio of positive to zero cells in the final binary models.

## RESULTS

### Ecological niche modelling

For the modelling of both *Mastomys awashensis* and *Stenocephalemys albipes*, 12 bioclimatic layers were selected based on multicollinearity analysis (Appendix 2): BIO1 (Annual mean temperature), BIO2 (Mean diurnal range), BIO4 (Temperature seasonality), BIO5 (Maximum temperature of warmest month), BIO6 (Minimum temperature of coldest month), BIO8 (Mean temperature of wettest quarter), BIO9 (Mean temperature of driest quarter), BIO14 (Precipitation of driest month), BIO15 (Precipitation seasonality), BIO16 (Precipitation of wettest quarter), BIO18 (Precipitation of warmest quarter), and BIO19 (Precipitation of coldest quarter). After data cleaning and spatial thinning, 10 occurrence points were used for *M. awashensis* and 65 occurrence points were used for *S. albipes*. Models with the lowest  $\Delta$  AICc values were selected as the final models for ENM analyses of each species – for *M. awashensis* this was Linear features with RM= 0.5 ( $\Delta$  AICc= 0), and for *S. albipes* this was Linear+Quadratic features with RM= 0.5 ( $\Delta$  AICc= 0). The models for *M. awashensis* and *S. albipes* returned AUC values of  $0.974 \pm 0.009$  and  $0.977 \pm 0.011$ , respectively, and TSS values of 0.735 and 0.801, indicating robust performance for both species. Mean diurnal range and temperature seasonality had high contribution to the models of both species (Table 1).

### *Stenocephalemys albipes* ENM

The ecological niche model for *S. albipes* (MSS threshold 0.525) showed that 20.704% of the study area is climatically suitable in the current time period (Image 3; Table 2). In both future time periods, scenarios, and GCMs, there was significant increase, with an average increase of 18.437% to  $39.141 \pm 3.695$  % in 2041–2060,

**Table 1. Variable contributions of each bioclimatic layer used in the analysis, for both species.**

Variable	Name	Percentage contribution		Permutation importance	
		<i>Stenocephalemys albipes</i>	<i>Mastomys awashensis</i>	<i>Stenocephalemys albipes</i>	<i>Mastomys awashensis</i>
BIO1	Annual mean temperature	41.2	0	0	0
BIO2	Mean diurnal range	15.4	27.7	12.8	18.2
BIO4	Temperature seasonality	28	47.6	38.8	74.2
BIO5	Max temperature of warmest month	0.1	0	0	0
BIO6	Min temperature of coldest month	0.1	3.8	0.6	0.1
BIO8	Mean temperature of wettest quarter	0.9	12.1	44.2	3
BIO9	Mean temperature of driest quarter	2	0.2	0.4	0.5
BIO14	Precipitation of driest month	0.5	1.9	0.4	2
BIO15	Precipitation seasonality	0.6	1	1.4	0.9
BIO16	Precipitation of wettest quarter	0.5	0.6	0.6	0.6
BIO18	Precipitation of warmest quarter	0.8	2.6	0.8	0.3
BIO19	Precipitation of coldest quarter	9.9	2.4	0	0.1

**Table 2. Changes in climatically suitable areas of both species (in percentage values).**

<i>Mastomys awashensis</i>				<i>Stenocephalemys albipes</i>			
Scenario	Time Period	CanESM5	MIROC-ES2L	Scenario	Time Period	CanESM5	MIROC-ES2L
-	Current	46.077%		-	Current	20.704%	
SSP2-4.5	2041–2060	0%	0%	SSP2-4.5	2041–2060	39.982	34.527
SSP2-4.5	2061–2080	0%	0%	SSP2-4.5	2061–2080	40.113	35.353
SSP5-8.5	2041–2060	0%	0%	SSP5-8.5	2041–2060	43.462	38.594
SSP5-8.5	2061–2080	0%	0%	SSP5-8.5	2061–2080	47.407	39.186

and a further increase of 1.373% to  $40.514 \pm 5.035$  % in 2061–2080. There was little difference in the percentage area of future climatic suitability between SSP2-4.5 and SSP5-8.5 (Image 3; Table 2), indicating that different future climate scenarios have little impact on the overall effect of climate change on this species.

The variables with the highest percentage contribution and permutation importance for this species were temperature seasonality (BIO4; 28% contribution, 38.8% p. imp.) and mean diurnal range (BIO2; 15.4% contribution, 12.8% p. imp.) (Table 1). Additionally, annual mean temperature (BIO1) had the highest percentage contribution to the model (41.2%), but showed 0 permutation importance, and similarly, mean temperature of the wettest quarter (BIO8) showed the highest permutation importance (44.2%), but had a very low percentage contribution to the model (0.9%).

In the current scenario, highest environmental suitability (>75%) according to climate was seen at a mean diurnal range (BIO2) of  $14.901 \pm 1.556$  °C, and

a mean temperature seasonality (BIO4) of  $114.903 \pm 28.698$  °C. In SSP2-4.5, representing a middle-of-the-road scenario, BIO2 underwent a slight decrease to a mean value of  $14.137 \pm 1.139$  °C in the 2041–2060 time period, and further to  $14.065 \pm 1.185$  °C in 2061–2080; BIO4 also decreased to a mean value of  $109.902 \pm 30.14$  °C in 2041–2060, and increased to  $111.027 \pm 32.302$  °C in 2061–2080. In SSP5-8.5, representing a fossil-fuelled economy, BIO2 underwent a decrease to a mean value of  $14 \pm 1.171$  °C in the 2041–2060 time period, and further to  $13.572 \pm 1.258$  °C in 2061–2080; BIO4, however, increased to a mean value of  $116.249 \pm 33.281$  °C in 2041–2060, and further to  $123.561 \pm 39.416$  °C in 2061–2080 (Table 3).

***Mastomys awashensis* ENM**

The ecological niche model for *M. awashensis* (MSS threshold 0.777) showed that 46.077% of the study area is climatically suitable in the current time period (Image 4; Table 2). In both future time periods, scenarios, and

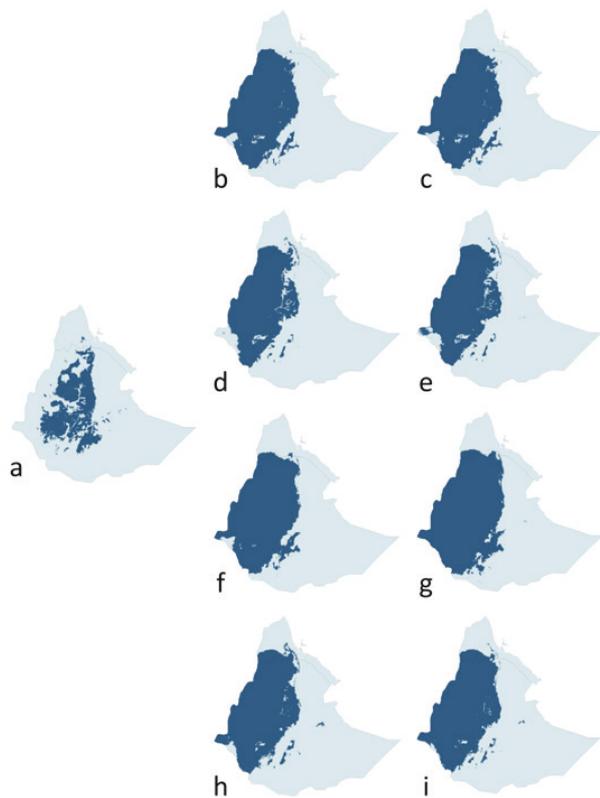


Image 3. Binary models output by MaxEnt for the distribution of *Stenocephalemys albipes*: a—current | b—2041–2060 in SSP2-4.5 and CanESM5 | c—2041–2060 in SSP5-8.5 and CanESM5 | d—2061–2080 in SSP2-4.5 and CanESM5 | e—2061–2080 in SSP5-8.5 and CanESM5 | f—2041–2060 in SSP2-4.5 and MIROC-ES2L | g—2041–2060 in SSP5-8.5 and MIROC-ES2L | h—2061–2080 in SSP2-4.5 and MIROC-ES2L | i—2061–2080 in SSP5-8.5 and MIROC-ES2L. Areas in dark blue represent high climatic suitability (i.e., the fundamental niche).

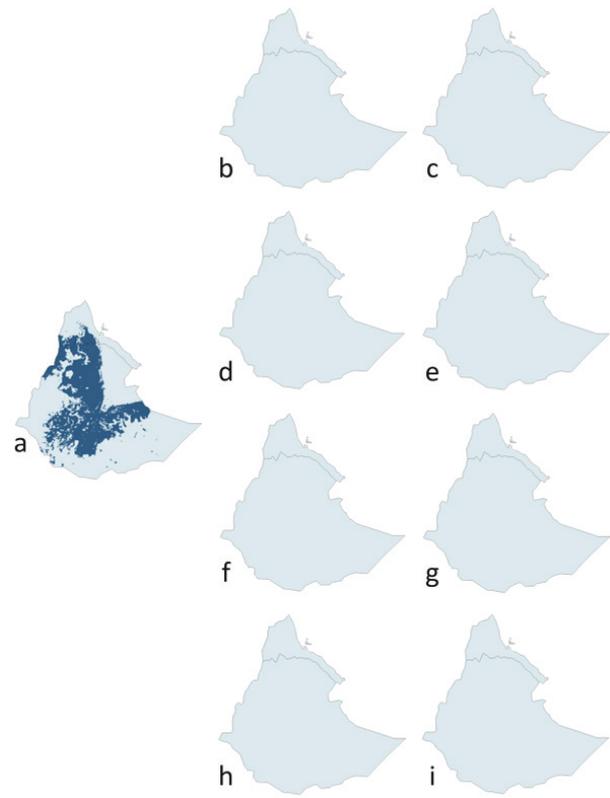


Image 4. Binary models output by MaxEnt for the distribution of *Mastomys awashensis*: a—current | b—2041–2060 in SSP2-4.5 and CanESM5 | c—2041–2060 in SSP5-8.5 and CanESM5 | d—2061–2080 in SSP2-4.5 and CanESM5 | e—2061–2080 in SSP5-8.5 and CanESM5 | f—2041–2060 in SSP2-4.5 and MIROC-ES2L | g—2041–2060 in SSP5-8.5 and MIROC-ES2L | h—2061–2080 in SSP2-4.5 and MIROC-ES2L | i—2061–2080 in SSP5-8.5 and MIROC-ES2L. Areas in dark blue represent high climatic suitability (i.e., the fundamental niche).

Table 3. Values for BIO2 (Mean diurnal range) and BIO4 (Temperature seasonality), averaged across both GCMs, for each time period and scenario for both species, at areas of high climatic suitability. Future values for *M. awashensis* are not given as it has 0 climatic suitability in all scenarios. Values are given as Mean ± standard deviation.

<i>Stenocephalemys albipes</i>			
Scenario	Time Period	BIO2	BIO4
-	Current	14.901 ± 1.556	114.903 ± 28.698
SSP2-4.5	2041–2060	14.137 ± 1.139	109.902 ± 30.14
SSP5-8.5	2041–2060	109.902 ± 30.14	14.065 ± 1.185
SSP2-4.5	2041–2060	14.065 ± 1.185	111.027 ± 32.302
SSP5-8.5	2041–2060	111.027 ± 32.302	14 ± 1.171
SSP2-4.5	2061–2080	14 ± 1.171	116.249 ± 33.281
SSP5-8.5	2061–2080	116.249 ± 33.281	13.572 ± 1.258
SSP2-4.5	2061–2080	13.572 ± 1.258	123.561 ± 39.416
SSP5-8.5	2061–2080	123.561 ± 39.416	14.935 ± 1.318
<i>Mastomys awashensis</i>			
Scenario	Time Period	BIO2	BIO4
-	Current	15.986 ± 1.075	136.481 ± 33.077

GCMs however, there was complete and total decline, resulting in 0% of the study area being climatically suitable by 2041–2060 and into the future (Image 4). This indicates that *M. awashensis* is extremely sensitive to climate change scenarios, and due to the effect of climate change alone, will lose all of its fundamental niche in the near future.

For this species, temperature seasonality (BIO4; 47.6% contribution, 74.2% p. imp.) and mean diurnal range (BIO2; 27.7% contribution, 18.2% p. imp.) were the highest contributors (Table 1). All the other variables had significantly lower percentage contribution and permutation importance.

In the current scenario, highest environmental suitability (>75%) according to climate was seen at a mean diurnal range (BIO2) of 15.986 ± 1.075 °C, and a mean temperature seasonality (BIO4) of 136.481 ± 33.077 °C (Table 3).

## DISCUSSION

Ecological niche models have often been used to model and project rodent distributions and niches, but a large proportion of these studies are restricted to species found in the Americas (Martínez-Salazar et al. 2012; Bean et al. 2014; Kubiak et al. 2017; Flores-Zamarripa & Fernández 2018; Urbina-Cardona et al. 2019; Pardi et al. 2020). African rodents have also been studied using ENM techniques; Taylor et al. (2015) showed that trends in the distribution of Afromontane rodents reflect changes in biomes predicted by past, present, and future climate scenarios. McDonough et al. (2015) showed in a hindcasting-based study on the Bushveld Gerbil *Gerbiscillus leucogaster* in Zambezi, that it is significantly impacted by changing climatic scenarios, but this was not explored in terms of future climate change. A general ecological niche model fitted by Martinov et al. (2020) created an estimation of the current predicted distribution of *Mastomys* species, including *M. awashensis*, however this analysis did not estimate the fundamental niche through binary modelling, and there was no projection to future climate scenarios.

Our results are in agreement with the findings of Martinov et al. (2020), where the current distributions show high likelihood (>0.8) in areas included under our predicted current fundamental niche. Our results also emphasise the importance of ecological niche modelling and future projection of ENM analyses, due to the severity of the impact of climate change on *M. awashensis* (Ortega-Huerta & Peterson 2008).

The two species in our study—*Mastomys awashensis* and *Stenocephalemys albipes*—show significant changes as a result of changing climate scenarios. The result of our study for *S. albipes* shows a percentage area of current climatic suitability of 20.704%, with an increase of 18.437% in the near future (2041–2060), and a further increase of 1.373% in the distant future (2061–2080) in both climatic scenarios. Despite the different perspectives SSP2-4.5 and SSP5-8.5 take in terms of socioeconomic scenarios, emissions, and concentrations of greenhouse gases, there was negligible difference between the two in the future predictions of the fundamental niche of this species, suggesting that while climate change positively impacts this species, there is little impact of specific climate pathways. This result is in line with conclusions drawn by McDonough et al. (2015), where it was shown that rodent niches expanded from the last glacial maximum (approximately 200,000 years BP) through the last interglacial period (approx. 130,000

to 118,000 years BP), to the present day, most likely due to increasing temperatures across the year. The decrease in predicted future mean diurnal range most suitable for this species when compared to the current time period shows that in both shared socioeconomic pathway scenarios, this species will favour slightly colder climates. This effect is very small, however, as the largest change in mean diurnal range is from current to the 2061–2080 time period, with a  $1.329 \pm 0.298$  °C decrease.

In the case of *M. awashensis*, the current niche is relatively large, with 46.077% appearing to be climatically suitable for this species; however, it appears to be incredibly sensitive to climate change events, as in all future scenarios and time periods, none of the study area (and also the rest of Africa) appeared to be climatically suitable. This is a massive and drastic change, which reflects the high sensitivity of this species to climate change. Seasonal variation in temperature and mean diurnal range of temperature are the most important predicting factors for this species, which leads to the inference that this species is likely to be most affected by temperatures getting generally warmer and less seasonally varied, which happens in both scenarios.

According to the MaxEnt model, both species had relatively wide areas of climatic suitability (Imgae 3, 4). For both species, the northern regions of Ethiopia and parts of southern Eritrea were climatically suitable—this included highland, some lowland regions of the Great Rift Valley, and some scattered sites in southeastern Ethiopia. *S. albipes* had climatically suitable regions in the highlands of northern, western, and central Ethiopia, including Tigray, Amhara, northern Oromia, Southern Nations, Nationalities, & Peoples' (SNNP), Addis Ababa, and eastern Benishangul-Gumuz regions. There are also some scattered suitable sites near Harari in Ethiopia, and Debub and Gash-Barka regions in Eritrea. In all future scenarios and time periods, this species' fundamental niche was seen to expand and move westward in Ethiopia and Eritrea, occupying the Tigray, Amhara, Benishangul-Gumuz, Oromia, Addis Ababa, Gambela, and SNNP regions in Ethiopia & Gash-Barka and Debub regions in Eritrea. Some scattered areas of suitability were also seen in the Eritrean & Ethiopian highlands and in the highlands south of Dire Dawa.

*M. awashensis* showed climatic suitability in Tigray, Amhara, eastern Benishangul-Gumuz, Oromia, SNNP, Addis Ababa, Harari, and some parts of northern Somali regions. In Eritrea, it showed high climatic suitability in Gash-Barka and Debub. For both species, the Eritrean and Ethiopian highlands formed a distinct geographical



barrier, and no areas of climatic suitability were present east of the hill range. Earlier studies of both species have shown them to be restricted to highland habitats (Corti et al. 2005; Mohammed et al. 2010; Meheretu et al. 2014), however, some later studies reported them to occur from lowlands as well (Habtamu & Bekele 2008; Lavrenchenko et al. 2010). Our study corroborates these with our current predicted niche expanding to lowland regions as well as highlands.

The results of the present study show the efficacy of ecological niche modelling in offering important insights into the potential geographic distributions of African rodents. Although *M. awashensis* is present and has areas of climatic suitability in protected areas, it is likely that there are no species-specific conservation measures in place. The eventual increase in anthropogenic impact on the natural areas will only decrease the chances of the species' survival in the future, as the impact of climate change alone is very large. It is important to plan ground-truthing of the sites shown as part of the fundamental niche of both this study's species in order to ascertain their true distribution, range, and realised niche, as this will help create better conservation strategies. It is imperative that species-specific conservation measures are set in place based on the results of said ground-truthing, including in situ conservation management, captive breeding, and planned reintroductions.

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**Appendix 1. Localities used in ENM analysis of *Stenocephalemys albipes* and *Mastomys awashensis*.**

Name	Latitude	Longitude	Locality	Reference
<i>Stenocephalemys albipes</i>	5.800	39.200	Kebre Mengist, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	6.217	37.667	Dega Done, Gemu-Gofa, SNNP, Ethiopia	Demeke et al. 2007
<i>Stenocephalemys albipes</i>	6.233	37.567	Mt Dorse, Chenckia, Gemu-Gofa, SNNP, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	6.383	38.583	Kebre Mengist, Sidamo, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	6.833	40.550	Jebo Samo, Bale, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	6.917	39.167	Gedeb Mts., Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	6.983	40.020	7 km SE of Goba, Bale, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	7.050	39.167	Webi river, north of Dodola, Arsi, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	7.100	39.767	Webi river, W of Dinshu, Bale, Ethiopia	Zerihun et al. 2012
<i>Stenocephalemys albipes</i>	7.117	39.733	5 km of W of Dinshu, Bale, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	7.133	39.717	Mount Gaysay, Bale, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	7.134	36.954	Gorka Bersa, Chebera-Churchura NP, Ethiopia	Demeke & Afework 2014
<i>Stenocephalemys albipes</i>	7.433	35.000	Godare forest, Tepi, Ethiopia	Lavrenchenko 2017
<i>Stenocephalemys albipes</i>	7.580	36.800	Seka, 3 Km N Of, Horo, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	7.600	38.450	Alage, Ethiopia	Agerie & Afework 2015
<i>Stenocephalemys albipes</i>	7.620	36.770	Buyo Kechema, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	7.650	36.800	Jiren Farm, Jimma, Ethiopia	Tadesse & Afework 2012
<i>Stenocephalemys albipes</i>	7.667	39.333	Albasso forest, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	7.750	36.730	Atro, Agaro, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	7.820	36.680	Agaro, 14 km by road SE of Mejo, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	7.833	39.333	Wodajo, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	7.917	39.283	Jawi Chilalo, Galama mtn, Arsi, Ethiopia	Mohammed et al. 2010
<i>Stenocephalemys albipes</i>	7.917	39.450	Mt Albasso, Camp Wodajo, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	8.155	35.525	Illubabor, W of Gore, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	8.183	35.367	Lemen, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	8.250	36.167	Yemenigisit Den Yebaja Chaka, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	8.280	36.900	Atenago, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	8.367	35.817	Wabo, 5 km of W of Sceccchi river, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	8.500	34.775	Addo, 7km SW of Dembidolo, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	8.517	39.200	Wonji Sugarcane, Qoboluto Tumsa, Ethiopia	Serekebirhan et al. 2011
<i>Stenocephalemys albipes</i>	8.917	38.583	Dima Goranda, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	9.017	35.250	Sido Were Wele, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	9.050	38.520	Berifeta Lemefa, near Holetta, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	9.067	38.650	Menagesha forest, Shoa, Ethiopia	Afework 1996
<i>Stenocephalemys albipes</i>	9.117	37.050	Bako, Shoa, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	9.517	38.217	Subagajo, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	10.333	37.833	Debra Markos, Gojjam, Amhara, Ethiopia	Ejigu & Afework 2013
<i>Stenocephalemys albipes</i>	10.494	39.611	Yetere forest, Ethiopia	Gezahegn et al. 2016
<i>Stenocephalemys albipes</i>	10.667	38.167	Debre Werk, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	10.667	37.917	Naziret M Alem, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	10.739	36.800	Arditsy forest, Awi zone, Ethiopia	Getachew & Afework 2015
<i>Stenocephalemys albipes</i>	10.846	38.675	Borena-Sayint NP, Ethiopia	Meseret & Solomon 2014
<i>Stenocephalemys albipes</i>	11.117	37.317	Amedamit Mount, Amhara, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	11.167	36.250	Pawe area, B. Gumuz, Ethiopia	Tilahun et al. 2012

Name	Latitude	Longitude	Locality	Reference
<i>Stenocephalemys albipes</i>	11.267	36.833	Dangila, Amhara, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	11.417	37.967	Shime, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	11.583	37.417	Bihar-Dar, Amhara, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	11.717	37.917	Mahdere Marayam, Gondar, Amhara, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	12.350	35.783	Alatish NP, Ethiopia	Tadesse & Afework 2008
<i>Stenocephalemys albipes</i>	12.617	37.483	Gondar, Amhara, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	12.633	37.500	NE of Angereb Dam, Gondar, Amhara, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	12.750	37.700	Yerer mountain forest, Shoa, Ethiopia	Yonas & Fikresilasie 2015
<i>Stenocephalemys albipes</i>	13.133	37.917	Debark, NE Gondar, Amhara, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	13.133	37.917	Semien Mts, Amhara, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	13.192	37.893	Debir, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	13.232	38.038	Semien NP, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	13.650	39.172	Hagere-selam, Ethiopia	Meheretu et al. 2012
<i>Stenocephalemys albipes</i>	14.166	37.309	Habesha Adi Goshu, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	14.183	37.305	Kunama Adi Goshe, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	14.210	36.766	Adebayetown, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	14.251	37.270	Kunama Adi Goshe, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	14.284	36.688	Kafta-Sheraro NP, Tigray, Ethiopia	Alembrihan & Srinivasulu 2019
<i>Stenocephalemys albipes</i>	14.291	36.677	Helet Coka, Ethiopia	GBIF
<i>Stenocephalemys albipes</i>	14.950	38.270	Mt. Kullu, Shambiko, Eritrea	GBIF
<i>Stenocephalemys albipes</i>	15.332	39.064	Nefasit, Eritrea	GBIF
<i>Stenocephalemys albipes</i>	11.083	36.850	Aquatimo forest, Gojjam, Ethiopia	Moges & Dessalegn 2015
<i>Mastomys awashensis</i>	9.000	40.167	Awash, Ethiopia	Lavrenchenko et al. 1998
<i>Mastomys awashensis</i>	7.833	38.717	S of Ziway Lake, Ethiopia	Corti et al. 2005
<i>Mastomys awashensis</i>	8.383	39.150	E of Koka Lake, Bati Qelo, Ethiopia	Lavrenchenko & Corti 2008
<i>Mastomys awashensis</i>	9.065	42.275	Nigaya Bobasa, Babile Sanctuary, Ethiopia	Lavrenchenko et al. 2010
<i>Mastomys awashensis</i>	13.668	39.175	Hagere-selam, Ethiopia	Meheretu et al. 2014
<i>Mastomys awashensis</i>	12.600	39.517	N of Lake Hashenge, Ethiopia	Mengistu et al. 2015
<i>Mastomys awashensis</i>	14.210	36.766	Near Adebaye Town, Kafta Sheraro National Park, Ethiopia	Alembrihan & Srinivasulu 2019
<i>Mastomys awashensis</i>	14.251	37.270	Kunama Adi Goshu, Kafta Sheraro National Park, Ethiopia	Alembrihan & Srinivasulu 2019
<i>Mastomys awashensis</i>	14.284	36.688	Helet Coka, Ethiopia	GBIF
<i>Mastomys awashensis</i>	14.287	36.679	Adebaye Geter, E of Himora, Ethiopia	GBIF
<i>Mastomys awashensis</i>	14.184	37.305	NW of Birkuta, Ethiopia	GBIF
<i>Mastomys awashensis</i>	14.168	37.310	Habesha Adi Goshu, Ethiopia	GBIF
<i>Mastomys awashensis</i>	7.2545	36.798	Gojeb River, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	7.4782	36.5334	Shebe, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	8.2331	37.5887	Gibe National Park, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	8.2338	37.5823	Gibe National Park, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	8.4651	39.1606	Lake Koka, Bati Qelo, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	8.6943	36.4149	Didessa River, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	8.8453	40.0119	Awash National Park, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	9.0586	42.2796	Babile Elephant Sanctuary, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	9.1478	42.2624	Babile Elephant Sanctuary, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	9.2249	34.8662	Dhati-Welel National Park, Ethiopia	Martynov et al. 2020



Name	Latitude	Longitude	Locality	Reference
<i>Mastomys awashensis</i>	9.2393	34.8653	Dhati-Welel National Park, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	9.2449	34.8644	Dhati-Welel National Park, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	9.5548	39.7818	Ankober, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	9.5554	39.7657	Ankober, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	11.0526	39.6481	Kombolcha, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	11.7525	37.9068	Gumara River, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	11.7797	37.7313	Gumara River, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	12.5492	39.6431	Adi Mancarre, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	12.6393	39.5383	Adi Aba Musa, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	12.6551	39.5816	Kube, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	13.1858	37.9671	Simien Mts National Park, Ethiopia	Martynov et al. 2020
<i>Mastomys awashensis</i>	14.0945	37.4575	Mai-Temen, Ethiopia	Martynov et al. 2020

Appendix 2. Correlation matrix resulting from the spatial multicollinearity test of the 19 bioclimatic variables used in the analysis.

Layer	BIO1	BIO2	BIO3	BIO4	BIO5	BIO6	BIO7	BIO8	BIO9	BIO10	BIO11	BIO12	BIO13	BIO14	BIO15	BIO16	BIO17	BIO18	BIO19
BIO1	1.000																		
BIO2	-0.031	1.000																	
BIO3	0.141	-0.489	1.000																
BIO4	-0.116	0.567	-0.951	1.000															
BIO5	0.633	0.554	-0.604	0.666	1.000														
BIO6	0.681	-0.599	0.745	-0.766	-0.123	1.000													
BIO7	-0.120	0.769	-0.906	0.958	0.688	-0.805	1.000												
BIO8	0.744	0.128	0.134	-0.128	0.471	0.486	-0.074	1.000											
BIO9	0.516	-0.258	-0.074	0.116	0.405	0.330	0.001	-0.053	1.000										
BIO10	0.754	0.312	-0.501	0.556	0.957	0.077	0.516	0.496	0.561	1.000									
BIO11	0.775	-0.399	0.701	-0.713	0.022	0.969	-0.695	0.578	0.326	0.186	1.000								
BIO12	-0.051	-0.627	0.767	-0.776	-0.660	0.555	-0.800	-0.076	-0.051	-0.534	0.464	1.000							
BIO13	0.042	-0.513	0.718	-0.769	-0.565	0.574	-0.758	-0.002	-0.055	-0.452	0.527	0.920	1.000						
BIO14	-0.079	-0.478	0.463	-0.377	-0.400	0.303	-0.461	-0.063	-0.002	-0.303	0.185	0.571	0.334	1.000					
BIO15	0.425	0.282	0.092	-0.180	0.246	0.274	-0.053	0.490	-0.064	0.210	0.393	-0.154	0.111	-0.402	1.000				
BIO16	0.004	-0.501	0.716	-0.762	-0.585	0.543	-0.747	-0.029	-0.075	-0.479	0.496	0.937	0.991	0.352	0.070	1.000			
BIO17	-0.077	-0.530	0.507	-0.421	-0.436	0.342	-0.510	-0.072	0.017	-0.329	0.215	0.626	0.378	0.984	-0.428	0.394	1.000		
BIO18	-0.170	-0.513	0.610	-0.637	-0.633	0.376	-0.653	-0.035	-0.244	-0.571	0.272	0.805	0.713	0.536	-0.150	0.728	0.577	1.000	
BIO19	0.070	-0.461	0.456	-0.417	-0.318	0.404	-0.486	-0.074	0.185	-0.183	0.335	0.631	0.547	0.418	-0.208	0.562	0.454	0.279	1.000







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ISSN 0974-7907 (Online) | ISSN 0974-7893 (Print)

April 2021 | Vol. 13 | No. 5 | Pages: 18099–18410

Date of Publication: 26 April 2021 (Online & Print)

DOI: 10.11609/jott.2021.13.5.18099-18410

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