Full title: Protected areas network is not adequate to protect a critically endangered East Africa Chelonian: Modelling distribution of pancake tortoise, Malacochersus tornieri under current and future climates

Short title: Protected areas network is not adequate to protect pancake tortoises

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ABSTRACT

While the international pet trade and habitat destruction have been extensively discussed as major threats to the survival of the pancake tortoise (*Malacochersus tornieri*), the impact of climate change on the species remains unknown. In this study, we used species distribution modelling to predict the current and future distribution of pancake tortoises in Zambezian and Somalian biogeographical regions. We used 224 pancake tortoise occurrences obtained from Tanzania, Kenya and Zambia to estimate suitable and stable areas for the pancake tortoise in all countries present in these regions. We also used a protected area network to assess how many of the suitable and stable areas are protected for the conservation of this critically endangered species. Our model predicted the expansion of climatically suitable habitats for pancake tortoises from four countries and a total area of 90,668.75 km$^2$ to ten countries in the future and an area of 343,459.60 - 401,179.70 km$^2$. The model also showed that a more significant area of climatically suitable habitat for the species lies outside of the wildlife protected areas. Based on our results, we can predict that pancake tortoises may not suffer from habitat constriction. However, the species will continue to be at risk from the international pet trade, as most of the identified suitable habitats remain outside of protected areas. We suggest that efforts to conserve the pancake tortoise should not only focus on protected areas but also areas that are unprotected, as these comprise a large proportion of the suitable and stable habitats available following predicted future climate change.

Keywords: Pancake tortoise, *Malacochersus tornieri*, species distribution modelling, suitable habitat, stable habitat, protected area, climate change
INTRODUCTION

Over the past few decades, there has been growing interest in species distribution models (SDMs) as fundamental tools for the studies of ecology, biogeography, and biodiversity conservation [1]. These models are used to enhance understanding of the factors that alter species distribution, which is critical for adjusting or designing appropriate conservation strategies and for predicting geographical distribution under current and future climatic scenarios [1–3]. Such adjustments and predictions are necessary because climate change poses a severe threat to the conservation of natural landscapes and species across the globe and is reported to be among the primary drivers of the current loss of global biodiversity [4–6]. Climate change has also been reported to accelerate shifts in range extension and the shrinkage of some species [3].

Tropical environments are widely recognized as biodiversity regions with ideal climatic conditions for the survival of a large proportion of reptile species. However, reptiles are currently facing severe threats because of climatic changes [3,7]. Climate change affects reptile biodiversity directly by altering reptile distribution patterns [3,4] and indirectly by threatening conservation areas, making them less habitable for reptile species [8]. For instance, Meng et al. [7] have reported that out of the 274 Tanzania reptile species they studied, 71% (194 reptile species) are vulnerable to climate change, suggesting a significant impact from climate on reptilian diversity. In a different study, predictions about the environmental responses of reptiles to future climatic conditions made using SDMs showed that four endemic Moroccan reptilian species are highly vulnerable to extinction in Morocco if climatic disturbance prevails as predicted [3]. The same study concluded that reductions in species-rich areas were also likely in future climatic scenarios [3].
Like other reptiles, *Malacochersus tornieri* hereafter referred to as the pancake tortoise, is not immune to the effects of climate change. The pancake tortoise is a small, soft-shelled, dorsoventrally flattened chelonian with discontinuous distribution in the scattered rocky hills and kopjes of the savannas of south-eastern and northern Kenya and northern, eastern, and central Tanzania [9–12]. The presence of pancake tortoises has also been reported in northern Zambia [13]. The areas in which pancake tortoises can be found are typically semi-arid; these areas are classified as having a dry climate, corresponding to both Zambezian and Somalian biogeographic regions, according to Linder et al. [14]. The Zambezian biogeographical region is a wider biogeographical region, spreading across Africa from Namibia to Tanzania, while the Somalian biogeographic region is considered a refugium for arid-adapted plants and a centre of endemism for reptiles [15,16].

Although the international animal trade and habitat destruction have been cited as the major threats to the survival of the pancake tortoise [10,11,17,18], the impact of climate change on the species remains largely unknown. Although the IUCN has identified climate change as one of the threats to pancake tortoise populations [10,11], to our understanding, there is no study that has assessed the impact of climate change on the future distribution pattern of pancake tortoises. The IUCN’s *Guidelines for Re-Introductions and Other Conservation Translocations* [19] has pointed out the need to understand and match the current and/or future climate of the destination area as a key climate requirement for introduced/translocated species. Considering that the pancake tortoise is critically endangered [9–12] and listed in the *CITES Appendix II* [13], understanding current and future climatic habitats suitable for this species could be an essential step in charting out a species conservation plan. Therefore, in this study, we used species distribution modeling...
(SDM) to determine current and future climatic habitats suitable for the pancake tortoise. We chose this method because SDM is the most widely accepted method of predicting climatically suitable habitats [20], which helps to avoid uncertainties in selecting areas for translocation while providing a higher chance of success [19–21].

While protected areas remain an essential approach for conserving biodiversity and protecting it against human-mediated threats [7,22], there are endangered species that inhabit areas outside of protected lands [23]. For example, 14.00% of threatened mammal species, 19.80% of birds, 10.10% of turtles and 26.60% of amphibians inhabit areas outside of the global protected area network [23]. Similarly, the majority of the pancake tortoise population in Kenya occupies habitats outside of protected areas [10]. With time, the ongoing impacts of climate change are expected to inflict changes to suitable habitats for pancake tortoises both within and outside of protected areas [8,24,25]. Therefore, understanding whether these protected areas will continue to be viable for protecting suitable habitats for pancake tortoises in the event of climate change is crucial to the development of specific and appropriate management and conservation plans for the species. Considering the species’ range varies under different climatic scenarios [1,2,26,27] while the size of most protected areas tends to remain the same [28], more species may eventually be placed at risk of extinction, especially threatened species [29]. Therefore, in order to align protected areas with suitable habitat ranges [30] and enhance the conservation of threatened species in different climatic scenarios [28], SDMs are essential.

SDMs have been used to assess the impact of climate change on the distribution of different species (e.g. [24,25,28,31]). These models use location data and environmental variables to predict the suitable distributional range of a species under climate change conditions [24,28], which is essential when designing adequate
species management programmes, as well as for endangered species conservation planning [32]. Although Bombi et al. [33] have used SDMs to model the distribution of all African tortoise species, including the pancake tortoise, their study did not predict the future distribution of the species. In this study, we used SDM to assess the distribution of pancake tortoises under current and future climatic conditions and to investigate how much of the climatically suitable habitat occurs within the Protected Areas Network in the Somali-Maasai and Zambezian biogeographical regions. Specifically, we assessed (i) the current and future climatically suitable areas for pancake tortoises, (ii) the occurrence of more stable areas over time and (iii) whether the protected areas will be viable for the conservation of the species.

The findings of this study could play a significant role in promoting the use of species distribution studies on species management approaches [34], including the proposal of suitable areas for translocation [20,35,36] and the establishment of nature reserves where species can be protected with minimal human intervention, as recommended by Malonza [10].

**METHODOLOGY**

**Study Area**

We predicted current and future climatically suitable habitats for pancake tortoises within the two major biogeographical regions of Africa in which the animal occurs naturally (Fig 1B). These regions are the Somali-Masai Regional Centre of Endemism (Somali-Masai RCE) and the Zambezian Regional Centre of Endemism (Zambezian RCE), both of which fall within the semi-arid climatic belt of eastern-south Africa [37,38]. The Somali-Masai RCE covers approximately 1.87 million km² of arid savannah, extending from north-eastern Somalia to the north-eastern
province of Kenya and reaching south through Tanzania into the valley of the Great Ruaha; it ends north of Lake Malawi [14,38,39]. The Somali-Masai RCE harbours approximately 4,500 plant species, of which 31.00% are endemic in the region [37,38]. The dominant vegetation in this region is Acacia spp. The Zambezian RCE (3.77 million km$^2$) extends in the northeast from the Somali-Masai RCE, and its distribution coincides with the Guinea savannas and woodlands and the Karoo-Namib RCE in the southwest [37,38]. It covers the whole of south-central Africa, from the Atlantic seaboard of Angola to the entirety of Mozambique, Tanzania and the uplands of Kenya and Ethiopia [14,39]. In terms of plant richness, it is more diverse than the Somali-Masai RCE, hosting about 8,500 plant species, out of which 54.00% are endemic in the region [37,38].

**Study Species**

The critically endangered pancake tortoise, *Malacochersus* [12], is a monotypic genus endemic to East Africa [10,40]. In East Africa, the pancake tortoise is restricted to Somali-Maasai and Zambezian vegetations [12,18,41–43]. In Tanzania, the species distribution is discontinuously scattered from the south-eastern shores of Lake Victoria to the Maasai Steppe and southward up to Ruaha National Park [10,12,18]. In Kenya, pancake tortoises are disjointly distributed from the northern to southern areas, passing though the central to south-eastern regions of the country [10,12]. In Zambia, the species has been recorded only in the northern Nakonde District that borders Tanzania [12,13]. The preferred micro-habitats for pancake tortoises are kopjes, rock outcrops and rocky hillsides [9,10,18] with an annual rainfall of 250 - 500 mm [42] and an elevational range of 400 - 1,600 m above sea level [44]. From the past two generations to the next generation, the observed and
expected population of pancake tortoises is expected to decline by 80.00%, with overexploitation and habitat destruction being the primary drivers [12]. Currently, the IUCN identifies biological resource use (intentional use) and agriculture and aquaculture (small-holder farming), as well as climate change (severe drought), as among the major threats to the habitat and population of pancake tortoises [12].

**Pancake Tortoise Occurrence Data**

We obtained occurrence data from the field, online databases and previous studies. On the ground, we collected pancake tortoise location data from eight sites in Tarangire National Park, three sites in the Babati district of the Manyara region, five sites in the Kondoa districts and two sites in Chemba district, both from the Dodoma region in central Tanzania.

We also downloaded pancake tortoise locations from the GBIF (https://www.gbif.org/) and VertNet (http://vertnet.org/). We used the rgbif [45] and rvertnet [46] R packages to download the occurrence data from the GBIF and VertNet, respectively. Both databases were accessed on 5 January 2020, and we downloaded all *Malacochersus tornieri* locations identified in Tanzania and Kenya. We did not find any pancake tortoise occurrences in Zambia in the two databases.

From the online databases, we excluded data with absent or incomplete coordinates and duplicate locations as well as non-natural locations, such as tortoise collection points, captive breeding sites and pet-animal release sites. Additionally, we searched for pancake tortoise locality records in the EMYSYSTEM Global Turtle Database [47] and then used Elevation Map (https://elevationmap.net/) to obtain location coordinates.
From previous studies, we extracted the names of the places where pancake tortoises were recorded/observed. For Tanzania, we used sites mentioned by Klemens and Moll [18] as well as point locations collected by Zacarias [48], while for Zambia we used point locations mentioned by Chansa and Wagner [13]. In Kenya, we obtained pancake tortoise sites from Malonza [10] and Kyalo [44]. After obtaining the site names, we used Google Maps (https://www.google.co.tz/maps/), Elevation Map (https://elevationmap.net/) and Mindat (https://www.mindat.org/) to obtain coordinates for each site. If the site was not available online, we contacted individuals currently or previously working in the area in order to obtain coordinates.

From all sources, we obtained data for a total of 224 occurrences, with most occurrence points falling within the current IUCN pancake tortoise distribution range (Fig 1C).

**Fig 1:** Current natural occurrence of pancake tortoise (*Malacochersus tornieri*) in the sampled areas. (A) Africa showing the buffered area (red) where location data was obtained. (B) Africa showing Zambezian and Somalian biogeographical region (red). (C) Pancake tortoise occurrences (black) with 1-degree wide buffer for each presence record (grey).

**Bioclimatic Variables**

Bioclimatic variables were obtained from the CHELSA database [49] with 30 arc-seconds resolution. The modelling domain comprised Zambezian and Somalian biogeographical regions [14]. These regions were selected because they represent the areas where pancake tortoises exist naturally [12,13,18,41–43]. We obtained variables for the two intermediate Representative Concentration Pathways (RCPs), RCP-4.5 and RCP-6.0, for the years 2050 (mean climate between 2041 and 2060).
and 2070 (mean climate between 2061 and 2080). These mid-impact RCPs are the
most desirable for future conservation planning, since they present a more realistic
path compared to the extreme RCPs (2.6 and 8.5) which may incorporate too many
uncertainties, causing projections to be unreliable. Variations in future scenarios
were also accessed through ten Global Circulation Models (GCMs) available in
CHELSA; we avoided those with high co-dependency [50], resulting in the selection
of MIROC5, CESM1-CAM5, IPSL-CM5A-MR, FIO-ESM, GISS-E2-H, CSIRO-Mk3-6-
0, GISS-E2-R, GFDL-ESM2G, MIROC-ESM-CHEM and MRI-CGCM3.
Variables were first submitted to a visual analysis, in which we deleted both the
precipitation of the warmest quarter (BIO 18) variable and the precipitation of the
coldest quarter (BIO 19) variable due to statistical artifacts, that may not represent
the continuous gradient of reality, in the study region. Those artifacts are generated
due to a difference in which quarter is the warmest (e.g. BIO18), causing the
precipitation of one cell to be the sum from January-February-March, while the very
next cell is the summed precipitation from February-March-April. We then masked
variables with one degree-wide buffer from each presence record (Fig 1A and C) and
excluded variables with a high variance inflation factor (VIF > 3) and highly
correlated variables (r > 0.7). This left us with six variables: the mean diurnal range
(BIO 2), the isothermality (BIO 3), the mean temperature of the wettest quarter (BIO
8), the precipitation of the wettest month (BIO 13), the precipitation of the driest
month (BIO 14) and the precipitation seasonality (BIO 15). These six variables were
used to calculate the climatic niche of the species. The selection routine was
performed using the usdm package [51] in R 3.6.2 [52]. Models were generated with
variables at 30 arc-seconds resolution, while the rasters used to project models were
upscaled at a factor of 10, resulting in rasters with a resolution of 2.5 arc-minutes.
Species Distribution Modelling

For the SDMs, we applied an ensemble method using the sdm package [53] in R 3.6.2 [52]. We implemented five algorithms using different approaches, with proper pseudo-absence selection, following Barbet-Massin et al. [54], as follows: MaxEnt, a machine-learning approach, with 1,000 randomly selected pseudo-absences; Multivariate Adaptive Regression Splines, a regression-based approach, with 100 randomly selected pseudo-absences; Multiple Discriminant Analysis, a classification approach, with 100 pseudo-absences randomly selected outside a surface-range envelope; Random Forest, a bagging approach, with 224 pseudo-absences randomly selected outside a surface-range envelope; and BIOCLIM, an envelope approach, with 100 randomly selected pseudo-absences. Algorithms were implemented using standard procedures within the sdm package [53]. Model evaluation was performed with ten runs of a four-fold cross-validation technique (75.00% training and 25.00% test). In each run, we calculated true skill statistics (TSSs) and the area under the receiver operating characteristic (AUC). To build ensemble models for each scenario, and after some pre-analysis, we selected models with TSSs and AUCs higher than the mean plus half the standard deviation. The mean AUC value was 0.958, with a standard deviation of 0.059 and a threshold equal to 0.988. The mean TSS value was 0.861, with a standard deviation of 0.112 and a threshold equal to 0.917. The selected models were binarized using the AUC threshold. This approach avoided the use of subjective thresholds. Ensembles were built as a committee average of binarized rasters. Afterwards, we normalized the resulting rasters. This returned an ensemble in which 1 represents sites where all models agree with presences, 0 represents sites where all models agree with absences and the values in between are subject to uncertainty, where 0.5 represents
cells with the highest uncertainty (i.e. half of the models agree with an absence, while the other half agree with a presence). We also built three potential refugees for the species by summing the normalized rasters from the five scenarios (current, RCP-4.5/2050, RCP-4.5/2070, RCP-6.0/2050 and RCP-6.0/2070). Then, we applied three thresholds, which were calculated by extracting all values greater than zero from the raster and obtaining the 90th, 95th and 99th quantiles (2.179, 2.850 and 3.930, respectively).

Furthermore, we calculated climatically suitable areas using a weighted method, multiplying the cell’s committee average by the cell area and summing all values within the rasters. This conservative method was intended to consider the uncertainty underlying each cell, as well as the different occupation proportions. We applied this method to all scenarios, as well as, to every country present in the Zambezian and Somalian biogeographical regions [14]. We also masked results from area calculations with the World Database on Protected Areas v. 3.1 polygons [36] to estimate the climatically suitable areas under protection in the regions, countries and scenarios. Area calculations were performed in R 3.6.2 [52].

RESULTS

Our model demonstrated high performance, with an average AUC of 0.958 (SD = 0.059) and an average TSS of 0.861 (SD = 0.112). Currently, in the Zambezian and Somalian biogeographical regions, the pancake tortoise has a more extensive range in Tanzania and Kenya than in other countries present in the region (Fig 2). Although there is currently no evidence of records of pancake tortoises in Angola and Ethiopia, surprisingly, the model predicted patches of climatically suitable habitats in those countries under the current climatic scenario (Fig 2). Additionally, the model revealed
that the current suitable distribution range of pancake tortoises is 90,668.75 km², with Kenya contributing 61.10% of the current total range, followed by Tanzania (30.32%), Ethiopia (5.03%) and Angola (3.55%) (Table 1). Considering future climatic scenarios, the SDM predicted that the pancake tortoise’s suitable habitat would not decrease. This was observed through the expansion of suitable habitats as predicted by RCP 4.5 and RCP 6.0 (Fig 2; Table 1). The model predicted that the current distribution range would expand by 303.95% in the year 2050 and 342.47% in the year 2070 for RCP-4.5 and by 278.81% in the year 2050 and 311.99% in the year 2070 under RCP- 6.0 (Table 1). Similar to in the current scenario, Kenya and Tanzania will continue to have a larger suitable area (Fig 2; Table 1) than other countries. However, the distributional range will expand from the current four countries to ten countries in the future (Table 1).

Fig 2. Distribution of pancake tortoise (*Malacochersus tornieri*) in the Somalia and Zambezian biogeographical regions. Current and future (2050 and 2070) climatic suitable habitat for pancake tortoise in the Zambezian and Somalia biogeographical regions considering six bioclimatic variables and two future climate scenarios. Warmer colours show more suitable areas, ranging from red to green.
Table 1. *Malacochersus tornieri* suitable area (km$^2$) in the countries present in the Zambezian and Somalia biogeographical regions for the current and future climate scenarios.

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<th>Current Protected</th>
<th>Future RCP 4.5 Total</th>
<th>Future RCP 4.5 Protected</th>
<th>Future RCP 6.0 Total</th>
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<td>366,257.22</td>
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<td>291.73%</td>
<td>342.47%</td>
<td>319.48%</td>
<td>278.81%</td>
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</table>
The highly suitable areas (indicated by higher committee averages) are currently present in Kenya and Tanzania (Fig 2), where the species occurs naturally. In the future, highly suitable habitats will expand into Ethiopia as well (Fig 2); however, the species has not yet been recorded in that country. Although there were observations of pancake tortoises in Zambia (Fig 1), our model predicted that the area is not climatically suitable for pancake tortoises in the current and future scenarios (Fig 2).

Considering protected lands, we found that a larger suitable habitat for pancake tortoises lies outside of the current Protected Areas Network in both current and future climatic scenarios (Table 1). Currently, 67.63% of the suitable pancake tortoise habitat lies outside of protected areas (Table 1). In the future, the protected suitable area for pancake tortoises will expand from 114,969.40 km$^2$ (in 2050) to 123,112.71 km$^2$ (2070) in RCP-4.5 and 104,437.30 km$^2$ (in 2050) to 117,672.83 km$^2$ (in 2070) in RCP-6.0 (Table 1), given the current Protected Area Network. However, the larger suitable habitat of pancake tortoises will continue to lie outside of protected areas in the future (RCP 4.5: 68.61% in 2050 and 69.31% in 2070; RCP 6.0: 69.59% in 2050 and 68.50% in 2070; Table 1).

We identified Kenya, Tanzania, Ethiopia and Angola as the countries that maintain the most stable habitat for pancake tortoises over time (Table 2). However, the highest stability occurs within Kenya, Tanzania and Ethiopia (Fig 3), with only Kenya having a highly stable habitat inside the protected areas (Table 2). The stable habitats for pancake tortoises within the current Protected Areas Network will continue to be smaller than those of habitats in unprotected areas (percentage of stable habitat present in protected areas: less stable [33.08%], average stability [27.97%] and highly stable [14.87%, present in Kenya only]; Table 2).
Fig 3. Potential climatic stable areas for the pancake tortoise in the Zambezian and Somalia biogeographical regions. (A) Location of stable areas in Africa (red sheds). (B) Stable areas in Angola. (C) Stable areas in Tanzania, Kenya and Ethiopia. The stable areas were obtained by considering three thresholds from the sum of the five normalized climatic scenarios (current, RCP4.5/2050, RCP4.5/2070, RCP6.0/2050 and RCP6.0/2070). The brighter red colour indicates the more stable site through time.

Table 2. Potential climatic stable areas/habitats (in km$^2$) for the pancake tortoise per each country present in the Zambezian and Somalia biogeographical regions.

<table>
<thead>
<tr>
<th>Country</th>
<th>Less stable</th>
<th>Mid stable</th>
<th>Highly stable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Protected</td>
<td>Total</td>
</tr>
<tr>
<td>Kenya</td>
<td>92,198.02</td>
<td>32,556.34</td>
<td>57,252.66</td>
</tr>
<tr>
<td>Tanzania</td>
<td>50,153.64</td>
<td>17,825.94</td>
<td>16,299.88</td>
</tr>
<tr>
<td>Zambia</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mozambique</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Malawi</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Angola</td>
<td>2,174.18</td>
<td>0</td>
<td>83.67</td>
</tr>
<tr>
<td>Namibia</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Botswana</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Somalia</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>19,904.86</td>
<td>4,004.25</td>
<td>8,513.63</td>
</tr>
<tr>
<td>Democratic Republic of Congo</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Burundi</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rwanda</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
DISCUSSION

Our SDM predicted that the suitable climatic habitat for pancake tortoises would be
less discontinuously scattered in the Zambezian and Somalian biogeographical
regions in the future than in current climatic scenarios (Fig 2). The disjointed
distribution of pancake tortoises was also observed in the countries in which they
currently exist naturally, which are Tanzania [9,12] and Kenya [10,12]. We further
observed that the distributional range of pancake tortoises would expand in the
future (Fig 2; Table 1). The expansion of the future distributional ranges of reptiles
has also been recorded by Houniet et al. [55] for Bradypodion occidentale,
González-Fernández et al. [56] for Thamnophis melanogaster, Fathinia et al. [57] for
Pseudocerastes urarachnoides and Sousa-Guedes et al. [58] for 13 different reptile
species.

Apart from area expansion, our model also predicted an increase in the number of
climatically suitable habitats in countries in which pancake tortoises do not exist
naturally from the current two to eight future countries, with Angola isolated in the far
west region (Fig 2; Table 1). The isolation of pancake tortoise populations is also
occurring within Tanzania [42] and Kenya [10], where the species exists naturally.
With pancake tortoises being non-migrant [10–12], this could be the reason for their
non-existence in the climatically suitable habitats present in the other countries
within the region. Furthermore, Malonza [10] has suggested that the absence of
pancake tortoises in potential habitats is mainly due to elevation, with species

<table>
<thead>
<tr>
<th>Country</th>
<th>Climatically Suitable Habitats</th>
<th>Total Presence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uganda</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>South Africa</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>164,430.70</td>
<td>54,386.53</td>
</tr>
</tbody>
</table>

**344**
occurring from 500 - 1,800 m above sea level [12]. As pancake tortoises prefer areas
featuring Precambrian rocks, the presence of other rock types between the suitable
habitats could act as a distribution barrier [13]. Therefore, this could be another
reason for the non-existence of pancake tortoises in some climatically suitable
habitats; however, the species may occur in the Zambezian floral region, provided
that suitable habitat is available [13,37].

Surprisingly, pancake tortoises have been reported to occur naturally in Zambia [13]
(Fig 1); however, our model did not indicate the presence of suitable habitats in
Zambia either under current or future climatic scenarios (Fig 2; Table 1). One reason
for this could be that the country is located at the limit of the climatically suitable
niche and thus has low climatic suitability, which, when applied at a threshold, turns
into an absence. This was affirmed by Chansa and Wagner [13], who have
mentioned that the sightings of pancake tortoises in Zambia were recorded at the
end of the pre-Cambrian rock basement. The absence of climatically suitable
habitats for pancake tortoises in Zambia in current and future scenarios could mean
that the animals recorded in the country were the result of the international animal
trade, as a result of which animals from East Africa were exported illegally from the
country [12]. However, this argument would require a genetic analysis for
confirmation.

Our model also predicted that Tanzania, Kenya, Ethiopia and Angola (Fig 3; Table 1)
will continue to have climatically stable habitats over time. As pancake tortoises have
not yet been recorded in Ethiopia and Angola, these areas could hold potential for
the translocation and introduction of the species. Additionally, we recommend
studies of these countries to assess the existence of pancake tortoises in them,
because the species is believed to exist in suitable habitats present in the
Zambezian and Somalian biogeographical regions [37],[13].

Protected areas are one of the most necessary tools in biodiversity conservation
[23]. However, the African Protected Areas Network does offer inconsistent
protection to tortoise species [33]. In the Zambezian and Somalian biogeographical
regions, only 32.37% of the current climatically suitable area for pancake tortoises
fall within protected areas, and this percentage is predicted to decline in the future to
30.41% - 31.50% (Table 1). Additionally, from 66.92% - 85.13% of the stable climatic
habitat is predicted to be outside of protected areas. Our results are inconsistent with
those of Bombi et al. [33], who have suggested that the established protected areas
in East Africa for wildlife conservation offer sufficient presentation for tortoises.
Across the entire range, only 22.60% of pancake tortoise habitats are protected [33].
In Kenya, only 5.00% of the pancake tortoise population is protected, while in
Zambia, none of the recorded species is within the Protected Area Network [12,13].
In Tanzania, only 4 out of 22 national parks have been recorded as harbouring
pancake tortoises. That the pancake tortoise’s suitable habitat is largely unprotected
in both the current scenario and the future increases the risk of overexploitation and
habitat destruction as it has already been recorded in Tanzania [18], Kenya [10,12]
and Zambia [12,13]. Additionally, the prevalence of ectoparasites such as ticks in the
pancake tortoise is higher outside of the protected area [59]; this adds more risk of
tick-borne diseases to the species.

Management Implications
With the current and future climatically suitable habitats being found beyond the
natural range of pancake tortoises, we recommend that studies be conducted in
areas where pancake tortoises do not exist to confirm the occurrence of the species. As White [37] and Chansa and Wagner [13] have pointed out, pancake tortoises could exist in the entire Zambezian and Somalian biogeographical regions, provided that suitable habitat is present; therefore, confirmatory studies on the existence of the species in the climatically suitable habitats are essential for conservation planning for the species. However, we caution that the existence of pancake tortoises is not solely dependent on the presence of climatically suitable habitats, as Malonza [10] has confirmed the non-presence of pancake tortoises in typical habitats for the species in Kenya. Furthermore, the available suitable and stable habitats outside of the current range could be used as baseline areas for the translocation and introduction of the species where necessary. Therefore, we support the IUCN [19] and Bellis et al. [20], who have suggested the importance of conducting SDMs before translocation and species introduction/re-introduction. Our model did not predict the existence of climatically suitable habitats for pancake tortoises in Zambia (Fig 2). Therefore, we recommend the maximization of conservation efforts in Zambia in order to maintain the recorded pancake tortoise populations, since they seem to be highly threatened. Furthermore, the presence of a large proportion of the climatically suitable habitat for pancake tortoises outside of protected areas could imply the need for more conservation efforts outside the protected range. These efforts might include the establishment of new protected areas aimed at biodiversity conservation to include suitable habitats for pancake tortoises and therefore minimize anthropogenic impacts on the species [10,35]. Since current increases to the Protected Area Network have rarely strategically considered global biodiversity maximization [23], establishing
protected areas within species suitable habitats could be one strategy for protecting
global biodiversity.

**Conclusion and Study Limitations**

The SDM in this study predicted the expansion of suitable habitats for pancake
tortoises in the future, which could lead to a stabilization of decreasing populational
trends or even their inversion into a trend of growth. However, the largest proportion
of these habitats will remain outside of the current Protected Area Network. This
poses more risk to the species, considering it is critically endangered. Therefore, we
do support the petition to upgrade the species from the current CITES Appendix II to
Appendix I.

The findings of this study should not be treated as ready-made for on-the-ground
application but could be used as one of many tools to help in conservation planning
of the species, considering climatic changes. This is because our results were mainly
based on climatic variables, and therefore, we did not consider non-climatic
variables. This decision was influenced by the fact that most of the species’
distributional changes are largely driven by climatic variables [60]. Although Giannini
et al. [61], de Araújo [6] and Palacio and Girini [61] have pointed out that the
inclusion of biotic factors significantly improves SDMs, we were unable to obtain
these data for our study. We recommend that future studies consider the inclusion of
pre-Cambrian rock (as it provides a preferred habitat for pancake tortoises), the
international pet trade, land-use changes and ecological interactions as variables.
However, in the current situation, it is difficult to obtain these data ready-made for
SDM, especially for future climatic scenarios. All in all, our study has provided the
foundation for future studies on pancake tortoise distribution.
ACKNOWLEDGEMENTS

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Fig 2