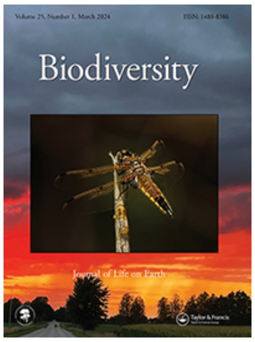


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# Exploring temperature and precipitation changes under future climate change scenarios for black and white rhinoceros populations in Southern Africa

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# Exploring temperature and precipitation changes under future climate change scenarios for black and white rhinoceros populations in Southern Africa

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**ABSTRACT**

Climate change is a potential human-induced threat to rhino populations and their habitat. Information on the effects of climate change on rhinoceros species can help manage and develop conservation plans to adapt to these changes. In this study, two climate change scenarios were used to predict temperature and precipitation changes in national parks in southern Africa and the effect those changes would have on black (*Diceros bicornis*) and white (*Ceratotherium simum*) rhinoceros populations. The study used the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCPs) 4.5 and 8.5, atmospheric $CO_2$ concentrations of 650 and 1370 ppm, for the years 2055 and 2085 to explore the temperature and precipitation changes. All spatial information was processed using Geographic Information Systems and statistical analysis. Results show the changing climate will have significant negative impacts on the probability of occurrence of both species. Temperature changes will affect these probabilities more than precipitation changes. All study parks will have zero probability of occurrence for the species throughout their ranges should conditions reach those represented by the RCP 8.5 scenario late in the century. Conservation activities for the rhinoceros should take into consideration the potential for temperature and precipitation changes modelled in this study.

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**KEYWORDS**
Rhinos; climate change; macroecological analysis; conservation; restoration

## Introduction

Africa has seen an increase in average monthly temperatures by 0.5–2°C over the past century, with an additional increase of more than 2°C expected on most of the African continent by the middle of the twenty-first century under a high emissions scenario of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (Carabine, Lemma, and Dupar 2014). The temperature changes associated with climate change, and human effects on the environment resulting in land use change (Barnes et al. 2017), have resulted in a massive redistribution of species (Pecl et al. 2017) in African ecosystems. Studying climate change and land-use influences on biodiversity is critical to develop conservation plans (Titeux et al. 2017), management plans and adaptation actions (West et al. 2009). Information on how species will respond to climate change can help managers develop adaptation strategies under various future climate change scenarios (Weiskopf et al. 2020). This study uses a macroecological assessment approach to analyse the impact of climate and land use change on rhinoceros habitats and the suitability of these areas for the black and white rhinoceros, which are critically endangered and near threatened, respectively (Harper et al. 2018).

Models have shown that the effects of climate change in Africa will include increased mean seasonal temperatures, decreased mean rainfall in most areas, increased frequency of El Niño Southern Oscillation (ENSO) in southern Africa, and increased frequency of severe weather anomalies (IPCC 2001, 2021). With a high confidence level, the IPCC (AR6) observes that mean temperature and hot extremes in Africa have emerged above natural variability relative to 1850–1900, and the rate of increase in surface temperature is more rapid than the global average increase (IPCC 2021). An increase in heat extremes and in the frequency of intense and heavy precipitation are also predicted for the continent with a high confidence level (IPCC 2021). The mean annual temperature in sub-Saharan Africa is expected to range between 26.4 and 27.6°C under RCP (representative concentration pathway) 4.5 and between 27.9 and 29.8°C under RCP 8.5 at the end of the century (Platts, Omeny, and Marchant 2015).

Adverse effects of the changing climate are evident in numerous species globally (Thomas et al. 2004), with

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more than one million species vulnerable to extinction by 2050 (Simmons et al. 2004). The extinction risk is expected to increase and accelerate with increasing temperatures (Root et al. 2003; Urban 2015). However, climate change effects on species are not likely to be the same across all taxa (Devictor et al. 2012; Erasmus et al. 2002).

In some cases, climate change threatens species with extinction and interferes with habitat processes (Parmesan 2006; Root et al. 2003; Simmons et al. 2004; Thomas et al. 2004; Walther et al. 2002). For species to survive, they must either adapt or migrate (Simmons et al. 2004), and for the rhinoceros, the ability to migrate is limited by human settlements. Therefore, this study has been undertaken to explore what future landscapes in the national parks (NPs) might look like for the African rhinoceros under various climate change scenarios, as very few studies have explored this idea (Pant et al. 2020).

Large-bodied animals like elephants may be the hardest hit by climate change (Martínez-Freiría et al. 2016). Rhinoceros lack a high surface area to dissipate heat, unlike elephants that have large ears and the ability to flap them and can use their trunk to spray themselves with water. Rhinos can increase water consumption, wallow, and rest in the shade to decrease their body temperatures (Dunkin et al. 2013; Mpakairi et al. 2020; Myhrvold, Stone, and Bou-Zeid 2012), but these strategies are not sufficient at higher temperatures. It is important to also understand that rhinoceros lack the ability to sweat, so while increased water consumption can help to cool them, they do not have natural evaporative cooling.

Eastern and southern Africa are home to more than 94% of the remaining black and white rhinos vulnerable to climate change (CITES 2022; Hulme 1996; IPCC 2001). The possible combined effects of temperature and precipitation changes on African rhinos have received minimal exploration (Mamba 2018). Using interacting stochastic agent-based and individual-based models, Haas and Ferreira (2015) estimate an extinction risk of southern white rhinos by 2036 in Kruger National Park and ranches in South Africa. Where the conservation of rhinos is concerned, the greatest effort has been invested in investigating the effects of poaching and habitat destruction on their survival (Mamba, Randhir, and Fuller 2020; Otiende et al. 2015; Thomas 2010). Studies investigating the possible impacts of temperature and precipitation changes on the species ranges of rhinos are limited, and this study fills this gap.

## Materials and methods

### *Study area*

The study area included South Africa, Namibia, Kenya, Zimbabwe, Swaziland, Botswana, Zambia, and Tanzania (Figure 1). As of December 2021, southern Africa, including South Africa, Namibia, Zimbabwe, and Kenya, was home to 92% and 80% of the white and black rhino populations, respectively (Ferreira et al. 2022). Kenya was included in the study because it is a primary range for the eastern subspecies of the black rhino, *D.b michaeli* (Ferreira et al. 2022).

The study focusses on NPs in southern Africa, including Kruger NP in South Africa, Etosha NP in Namibia, Hwange NP in Zimbabwe, Tsavo West NP in Kenya, and Hlane Royal NP in eSwatini. Kruger NP is South Africa's most extensive and flagship park, with an area of approximately 19,000 $km^2$ (De Vos et al. 2001; Venter, Scholes, and Eckhardt 2003). Etosha NP is in the north-central part of Namibia, covering 22,915 $km^2$ (Turner and Getz 2010). Hwange NP in Zimbabwe has an area of 14,600 $km^2$. Tsavo West NP is located in southeastern Kenya, covering an area of 9065 $km^2$. Hlane Royal NP is found in the northeastern part of eSwatini, in the Lowveld region, with 220 $km^2$.

The landscapes of the NPs are highly varied from an ecological perspective. Kruger NP is in the semiarid region of South Africa, with 35 landscape types within the park (Gertenbach 1983), and the park is already seeing evidence of climate change impacts on flora and fauna (Dube and Nhamo 2020). Etosha NP is in the dryland systems of Africa, comprising a series of saline pans in the region and a veterinary cordon fence at the southern and eastern borders of the park (Turner et al. 2022). Hwange NP is a semiarid dystrophic savanna facing increasing climate change impacts, especially drought severity (Chamaillé-Jammes, Fritz, and Murindagomo 2007). Tsavo NP is a lowland savanna with a semiarid climate and is experiencing the impacts of climate change through frequent and extended drought events (Sheriff and Mash 2022).

### *Methods*

#### *Spatial analyses*

Spatial data were analysed using Environmental Systems Research Institute (ESRI's) ArcMap version 10.5.1. Africa's annual mean temperature and precipitation raster files were used with the Geographic Coordinate System (GCS)–World Geodetic System (WGS) 1984 projection. The raster files had a resolution of 30 arc seconds (~ 1 km). Two climate change scenarios, with atmospheric $CO_2$ concentrations of 650 and 1370 ppm (RCPs 4.5 and 8.5, respectively), were analysed for two

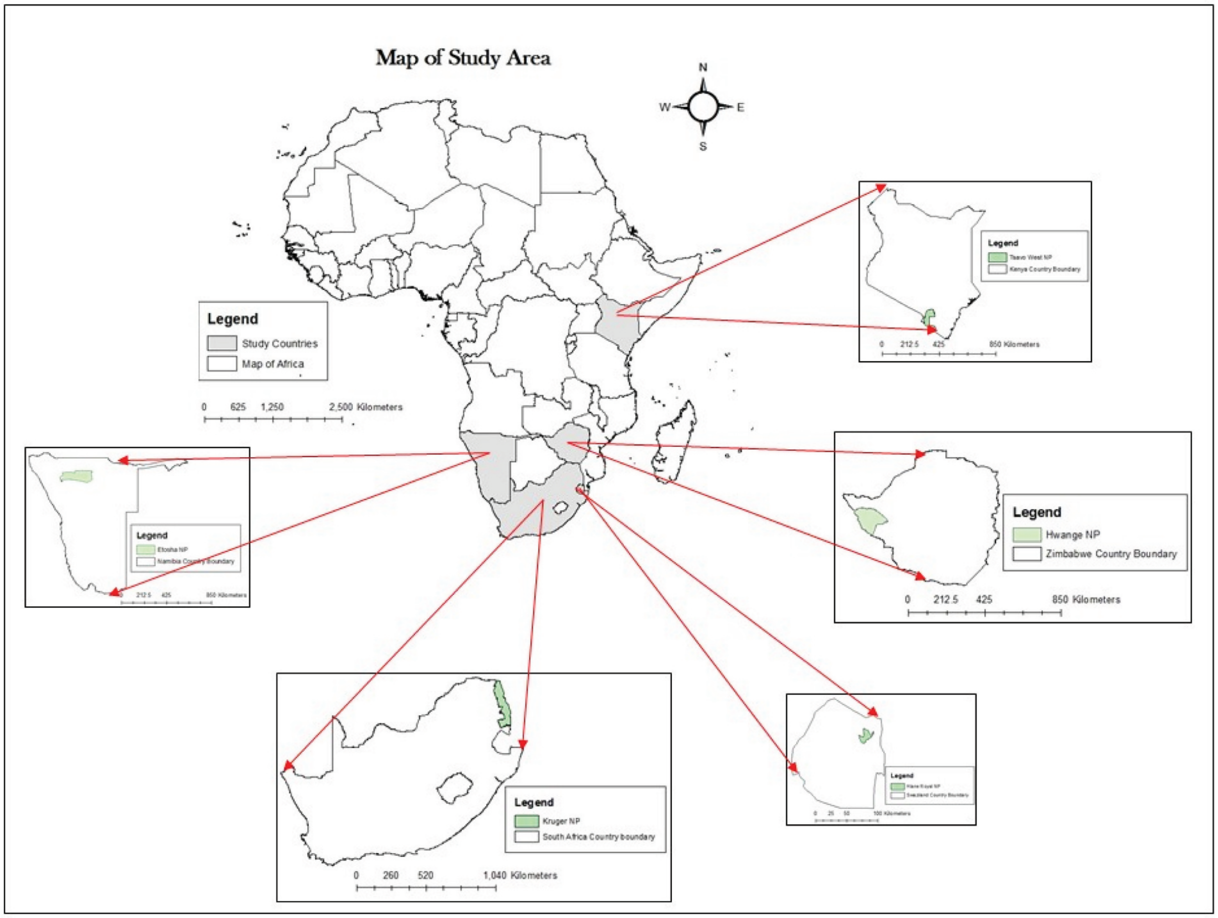


Figure 1. Study area, east and Southern Africa. NP: national park.

time periods (mid-century, 2055; and late century, 2085). The annual mean temperature and annual precipitation raster layers were clipped to the study parks to assess the temperature and precipitation patterns in the parks under the two climate change scenarios throughout the century.

### Probability of habitat suitability

The aim was to estimate the probability that the species will be present in or can use the NPs under future climatic conditions, conditional on two climate variables: annual mean temperature and annual precipitation. While exact measures are challenging to implement, we quantify the rhinos' probability of future occurrence based on potential changes predicted in climate variables where 1 represents 100% probability of habitat suitability, and 0 represents 0% habitat suitability. While extremes of these variables are helpful predictors of impacts on large mammals, we focussed on only the average conditions in deriving a probability of habitat suitability. Incorporating extremes will also require detailed uncertainty analysis that is beyond the scope of this study. We calculated the habitat suitability probabilities using the sample presence points and baseline climatic conditions. Using ArcMap 10.5.1 software (ESRI), the sample presence points (300 points) were overlaid with local annual mean temperature and precipitation data layers for the entire Southern Africa region. The extracted values were then used to create frequency graphs by classifying temperature and precipitation values into ranges with the corresponding number of occurrences within each range. The range with the highest number of occurrences was assigned a maximum probability value. A polynomial model was used to fit the data as it resulted in a better fit. Similar non-linearity in response curves is employed in habitat suitability assessment for land use and climate drivers (Pant et al. 2021).

## Data

### Species presence data

Species presence data were obtained from the Global Biodiversity Information Facility (GBIF 2017) databases as global positioning system (GPS) coordinates for individual animals. The GBIF is the largest repository of primary biodiversity data for this region (Anderson et al. 2016), and it is therefore used for many macroecological studies and correlates well with International Union for Conservation of Nature (IUCN) datasets (Alhajeri and Fourcade 2019). The records were based on human observation and included 136 black rhino presence points and 164 white rhino presence points. These points were saved as comma-delimited files in Microsoft Excel and made into point shapefiles in ArcGIS, which were then used to generate presence maps. The sites mapped covered South Africa, Namibia, Kenya, Zimbabwe, Swaziland, Botswana, Zambia, and Tanzania. Because of the level of sensitivity in rhino information, particularly the location of individual animals, it was challenging to obtain more data to increase the sample size. The estimates derived from small sample points may not reflect some hotspots of dense rhino populations and could be improved with more monitoring in the future.

*Climate data (historical and predicted).* Future climate predictions were obtained from the AFRICLIM database. The data were derived from climate surfaces produced from multi-model ensembles over predictions by eight Global Climate Models (GCMs) (Canadian Centre for Climate Modelling and Analysis – Canadian Earth System Model 2 (CCCma-CanESM2), Centre National de Recherches Météorologiques Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique – Climate Model ver. 5 (CNRM-CERFACS-CM5), Irish Centre for High-End Computing – European Consortium – Earth Systems Model (ICHEC-EC-EARTH), Model for Interdisciplinary Research on Climate – version 5 (MIROC-MIROC5), Met Office Hadley Centre – Hadley Centre Global Environment Model 2 – Earth System (MOHC-HadGEM2-ES), Max Planck Institute – Earth System Model – Low Resolution (MPI-ESM-LR), Norwegian Climate Center – The Norwegian Earth System Model Intermediate Resolution (NCC-NorESMI-M), National Oceanic and Atmospheric Administration-Geophysical Fluid Dynamics Laboratory – Earth System Model (NOAA-GFDL-ESM2G)). Using the two climate scenarios, RCP 4.5 and RCP 8.5, within the GCM, this study leveraged work from the MiniCAM modelling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI). This work represents a scenario where various technologies and strategies are employed to reduce greenhouse gas (GHG) emissions, stabilizing the total radiative forcing before 2100 (Clarke et al. 2007). The RCP 4.5 projected atmospheric $CO_2$ concentration is set at 650 ppm (Moss et al. 2010) and uses a modelled global temperature anomaly of 2.4°C above preindustrial temperatures (Rogelj, Meinshausen, and Knutti 2012). The RCP 8.5 scenario was derived by the Model for Energy Supply Systems And their General Environmental Impact (MESSAGE) modelling team's work and the work of the Integrated Assessment Framework at the International Institute for Applied Systems Analysis (IIASA) team in Austria. This scenario represents high GHG concentration levels at 1370 ppm by 2100 (Moss et al. 2010), resulting in a temperature anomaly of 4.9°C above preindustrial temperatures (Rogelj, Meinshausen, and Knutti 2012). The ensembles representing the two scenarios were dynamically downscaled by the Swedish Meteorological and Hydrological Institute – Rossby Centre Regional Atmospheric Climate Model v.4 (SMHI-RCA4) and Canadian Regional Climate Model 4 (CanRCM4) regional climate models (RCMs). RCM outputs were debiased using high-resolution baselines from Climatic Research Unit (CRU), WorldClim, Tropical Application of Meteorology Using Satellite Data and Ground-Based Observations (TAMSAT), and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Platts, Omeny, and Marchant 2015). The mean of the ensemble was used in the analyses because it can be expected to outperform individual ensemble members, thus providing an improved 'best estimate' forecast.

The baseline, mid-century, and late-century change factors were based on Platts, Omeny, and Marchant (2015). Two bioclimatic variables representing annual trends were included in the analyses: annual mean temperature and annual mean precipitation. These bioclimatic variables were used because they are biologically meaningful and are often used in ecological modelling to study the effects of past and future climate change on species distribution (Hijmans et al. 2005). Data were downloaded as raster files with a resolution of 30 seconds (~1 $km^2$) (Platts, Omeny, and Marchant 2015). Raster files representing probabilistic forecasts of global urban land cover change from 2000 to 2030 were downloaded from NASA's EarthData online database (2015). The grids had a resolution of 2.5 arc minutes. The final results included information on habitat suitability based on climatic factors using sites where rhinos were identified.

## Results

### Climatic changes in the parks

Historical baseline data from 1975, as averaged from 1961–1990, provided a reference point for the changes in temperature and precipitation expected in the study parks in the mid- and late century under the two modelled scenarios, RCPs 4.5 and 8.5 (Table 1). All parks show increasing temperatures spatially, although the degree of increase varied among parks (see SF1 to SF5 in the Supplementary material). The most substantial increases were observed in Etosha and Hwange NPs (Table 1). A 2.4°C increase mid-century was observed under RCP 4.5, and increases by 5.2 and 5.1°C, respectively, late in the century under RCP 8.5. Hlane and Tsavo West NPs will experience the lowest temperature increases of 1.9 and 2°C, respectively, by mid-century under RCP 4.5, and of 4.1 and 4°C, respectively, by the late century under RCP 8.5. Kruger NP's average temperature will increase by 2.1 and 4.5°C by mid-century with RCP 4.5 and by late century with RCP 8.5, respectively. All parks show large increases in temperature under the RCP 8.5 scenario by the late twenty-first century.

The amount of precipitation received by the four parks in the southern African continent will continue to decrease as the century progresses and as $CO_2$ levels in the atmosphere increase. The opposite is expected for Tsavo West NP in the east of the continent; this park will become wetter as the century progresses and will receive the highest amounts of rainfall under the conditions represented by RCP 8.5 late in the century.

**Table 1.** Temperature and precipitation changes under the two climate change scenarios in selected rhino parks.

| Park | Year | Representative Concentration Pathways (RCP) | ΔT* | ΔP* |
|---|---|---|---|---|
| Kruger | 2055 | 4.5 | 2.1 | −36 |
| | | 8.5 | 2.7 | −24 |
| | 2085 | 4.5 | 2.5 | −41 |
| | | 8.5 | 4.5 | −73 |
| Etosha | 2055 | 4.5 | 2.4 | −14 |
| | | 8.5 | 3.2 | −20 |
| | 2085 | 4.5 | 2.5 | −8 |
| | | 8.5 | 5.2 | −43 |
| Tsavo | 2055 | 4.5 | 2.0 | 39 |
| | | 8.5 | 2.5 | 38 |
| | 2085 | 4.5 | 2.3 | 52 |
| | | 8.5 | 4.0 | 90 |
| Hwange | 2055 | 4.5 | 2.4 | −11 |
| | | 8.5 | 3.1 | 0 |
| | 2085 | 4.5 | 3.0 | −27 |
| | | 8.5 | 5.1 | −28 |
| Hlane | 2055 | 4.5 | 1.9 | −21 |
| | | 8.5 | 2.5 | −16 |
| | 2085 | 4.5 | 2.4 | −38 |
| | | 8.5 | 4.1 | −54 |

*ΔT = change in average annual temperature compared to 1970 (average of 1961–1990), in °C. ΔP = change in annual precipitation compared to 1970, in mm.

### Kruger NP

The temperature range in Kruger NP is expected to change from current temperatures of 19.9–25.0°C to 21.9–27.2°C or 22.5–27.8°C under RCPs 4.5 and 8.5, respectively. The park's average temperature under the two scenarios will be 24.6°C for RCP 4.5 and 25.2°C for RCP 8.5. These average temperatures represent increases of 2.1 and 2.7°C, respectively, from the baseline of 22.5°C. Late in the century, the ranges are expected to be 22.3–27.7°C under RCP 4.5 or 24.2–29.7°C under RCP 8.5. The average temperatures at this time will be 25 and 27°C under RCPs 4.5 and 8.5, respectively. These represent increases by 2.5 and 4.5°C from the baseline.

Kruger NP will face increasing temperatures from the northernmost tip towards the south as the century progresses and as atmospheric $CO_2$ levels increase. The temperature increases of about 4.5°C anticipated late in the century under RCP 8.5 will result in the temperature in the northern half of the park reaching unprecedented levels. This park's precipitation range is expected to change from 415–971 mm under current conditions to 382–934 or 397–946 mm mid-century under RCPs 4.5 and 8.5, respectively. The park's average precipitation under the two scenarios will be 615 mm for RCP 4.5 and 627 mm for RCP 8.5. These averages represent decreases of 36 and 24 mm, respectively, from the baseline of 651 mm under the two scenarios. Late in the century, the ranges are expected to be 382–927 mm under RCP 4.5 or 354–889 mm under RCP 8.5. The park will have an average precipitation of 610 and 578 mm, respectively, under the two scenarios. These represent decreases by 41 and 73 mm from the baseline. As the century progresses and $CO_2$ levels increase, the amount of precipitation received by Kruger NP is expected to decrease, thereby making the park drier. This drying trend will move progressively from the north towards the park's southern parts.

### Etosha NP

As the century progresses, the temperature range in Etosha will change from 20.9–23.2°C at baseline to 23.2–25.7°C or 24.0–26.5°C by mid-century under RCPs 4.5 and 8.5, respectively. The average temperature under these scenarios will be 24.5°C for RCP 4.5 and 25.3°C for RCP 8.5. These are increases of 2.4 and 3.2°C, respectively, from the baseline of 22.1°C. Later in the century, the park's temperature will range from 23.7 to 26.2°C under RCP 4.5 or from 25.9 to 28.7°C under RCP 8.5. At this time, the average temperature in the park will be 25.0–27.3°C, respectively, which represents increases by 2.5 or 5.2°C from the baseline.

Etosha NP will experience record-level temperatures later in the century should the atmospheric $CO_2$ levels reach those represented by RCP 8.5. The precipitation range in Etosha NP is expected to change from 326–557 mm in the baseline to 309–548 or 303–542 mm mid-century under RCPs 4.5 and 8.5, respectively. The park's average precipitation will be 428 mm under RCP 4.5 and 422 mm under RCP 8.5. These averages represent decreases of 14 and 20 mm from the baseline of 442 mm under the two scenarios. Late in the century, the ranges are expected to be 314–555 mm under RCP 4.5 or 281–517 mm under RCP 8.5. The park will be receiving average precipitation of 434 and 399 mm, respectively, under the two scenarios. These represent decreases by 8 and 43 mm, respectively, from the baseline.

In addition, the western portion of the park will become drier as the century progresses and $CO_2$ levels in the atmosphere increase. This drying trend is expected to continue towards the eastern part of the park, with a substantial decrease in precipitation, by 43 mm, in the park's average precipitation in 2085 under the RCP 8.5 scenario, which will result in a significant portion of the park's western half becoming drier.

### Tsavo West NP

The temperature range in Tsavo West NP is expected to change from 18.0–25.7°C, the current baseline, to 19.9–27.5°C or 20.6–28.1°C mid-century under RCPs 4.5 and 8.5, respectively. The park's average temperature will be 24.1°C for RCP 4.5 and 24.6°C for RCP 8.5. These average temperatures represent increases of 2.0 and 2.5°C, respectively, from the baseline average of 22.1°C. Later in the century, the ranges are expected to be 20.3–27.9°C under RCP 4.5 or 22.1–29.6°C under RCP 8.5. The average temperatures under the two scenarios will be 24.4 and 26.1°C, respectively. These represent increases by 2.3 and 4.0°C from the baseline, respectively. Tsavo West NP will warm progressively from the north-eastern parts towards the south. The temperature increase will be about 4.0°C under the RCP 8.5 scenario, and by 2085, the temperatures in the park will be well beyond all previous recorded levels.

Tsavo West's precipitation range is expected to change from 570–1259 mm at baseline to 611–1306 or 615–1307 mm mid-century under RCPs 4.5 and 8.5, respectively. Under these scenarios, the average precipitation will be 899 and 898 mm, respectively. These averages represent increases of 39 and 38 mm, respectively, from the baseline average of 860 mm. Later in the century, the ranges are expected to be 623–1320 mm under RCP 4.5 or 657–1358 mm under RCP 8.5. The average precipitation will be 912 or 950 mm, respectively, under the two scenarios. These represent respective increases of 52 and 90 mm from the baseline.

Unlike the other parks in southern Africa, Tsavo West, in the eastern part of the continent, is expected to become wetter as the century progresses and $CO_2$ levels increase. Annual mean temperature increases in this park will be coupled with an increase in the park's average precipitation. While the overall precipitation amounts in the park are likely to increase, some portions at the centre of the park will become drier. This drying trend will be more pronounced should the conditions reach those represented by the RCP 8.5–2085 scenario.

### Hwange NP

In Hwange NP, the temperature range will change from 20.8–23.4°C at baseline to 23.1–25.8°C or 23.8–26.5°C mid-century under RCPs 4.5 and 8.5, respectively. The average temperatures for these two scenarios are 24.5°C under RCP 4.5 or 25.2°C under RCP 8.5. These averages represent increases of 2.4 and 3.1°C, respectively, in the park's temperature from the baseline temperature of 22.1°C. Later in the century, the ranges are expected to be 23.7–26.4°C or 25.8–28.6°C under RCPs 4.5 and 8.5, respectively. At this time, the park's average temperature will be either 25.1°C under RCP 4.5 or 27.2°C under RCP 8.5. These represent increases by 3.0 and 5.1°C, respectively, from the baseline. If atmospheric $CO_2$ levels reach those represented by the RCP 8.5–2085 scenario, the 3.0°C increase in the mean temperature of the park anticipated under this scenario will result in most parts of the park experiencing unprecedented high temperatures.

The precipitation range in Hwange NP is expected to change from 462–658 mm at baseline to 452–645 or 461–658 mm mid-century under RCPs 4.5 and 8.5, respectively. Under these scenarios, the average precipitation will be 549 and 533 mm, respectively. These represent decreases by 11 and 27 mm from the baseline of 650 mm. Later in the century, the ranges are projected to be 441–626 mm under RCP 4.5 or 437–626 mm under RCP 8.5. The averages will be 560 and 532 mm, respectively, under the two scenarios. These represent decreases by 0 and 28 mm from the baseline, respectively.

As the century progresses, the park's decreasing amount of precipitation will make the southern parts increasingly drier. This drying pattern will gradually progress from the south towards the park's northern parts. This drying trend will be more pronounced late in the century under scenario RCP 8.5–2085 when there will be a significant reduction in precipitation in the park.

### Hlane Royal NP

The temperature range in Hlane Royal NP is expected to change from 21.9–22.7°C at baseline to 23.7–24.6 or 24.3–25.2°C by mid-century under RCPs 4.5 and 8.5, respectively. The average temperature under the two scenarios will be 24.2°C under RCP 4.5 or 24.8°C under RCP 8.5. These represent increases of 1.9 and 2.5°C, respectively, in the park's temperature from the baseline of 22.3°C. Late in the century, the ranges are expected to be 24.2–25.1°C under RCP 4.5 or 26.0–26.8°C under RCP 8.5. The average temperatures will be 24.7 or 26.4°C under the two scenarios. These represent increases by 2.4 and 4.1°C from the baseline, respectively.

As in most of the other parks, precipitation received in Hlane Royal NP is expected to decrease as the century progresses and $CO_2$ levels in the atmosphere increase. In 2055, the precipitation received in the park is expected to range between 633 and 688 mm or between 639 and 692 mm under RCP 4.5 and RCP 8.5, respectively. These values can be compared to the baseline range of 653–711 mm. The two RCPs in 2055 will result in decreases by 21 and 16 mm, respectively, in the park's precipitation compared to that in the baseline scenario. In the late century, the precipitation will range between 616 and 671 mm or between 601 and 655 mm under RCPs 4.5 and 8.5, respectively. These represent further decreases of 38 and 54 mm, respectively.

### Rhinoceros tolerance within NPs under climate change scenarios

The current rhinoceros populations and sample presence points were used to estimate the species' tolerance of the two bioclimatic variables, annual mean temperature and annual precipitation, using the baseline conditions. It was found that rhino occurrences were greatest between temperature ranges of 12–24.1°C with an average of 20.8°C and 15.4–23.8°C with an average of 20.6°C for black and white rhinos, respectively (Table 2). Black rhinos tolerate a wider temperature range compared to their white counterparts. White rhinos appear to prefer more moderate temperatures compared to their black counterparts.

**Table 2.** Descriptive statistics of temperature and precipitation in black and white rhino occurrence sites, derived from 136 black and 164 white rhino presence points.

| | Black rhino | | White rhino | |
|---|---|---|---|---|
| | Temperature (°C) | Precipitation (mm) | Temperature (°C) | Precipitation (mm) |
| Minimum | 12.0 | 149 | 15.4 | 392 |
| Maximum | 24.1 | 1955 | 23.8 | 1452 |
| Range | 12.1 | 1806 | 8.4 | 1060 |
| Mean | 20.8 | 704 | 20.6 | 719 |
| Std. error | 0.21 | 24.11 | 0.15 | 12.59 |
| Std. deviation | 2.44 | 281.10 | 1.94 | 161.20 |
| Sample variance | 5.93 | 79,034 | 3.77 | 25,990 |

Concerning precipitation, black rhinoceros occurrences were found in regions that receive between 149 and 1955 mm of precipitation, with an average of 704 mm. Similarly, white rhinoceros were found in areas that receive between 392 and 1452 mm of precipitation, with an average of 719 mm (Table 2).

### The relationship between annual mean temperature and annual precipitation in black and white rhino occurrence sites

The relationship of annual mean temperature and annual precipitation with species' occurrence at the NP sites is non-linear. The relationship was best represented by cubic polynomial functions (Figure 2). For both species, at temperatures below 22°C, a steady increase in the temperature results in an increase in the precipitation. Above 22°C, an increase in temperature results in an exponential rise in precipitation.

The temperature range of 22–23°C has an occurrence probability of 1 (or 100%) for both the black and white rhinos. For precipitation, the ranges 330–510 mm and 605–710 mm have an occurrence probability of 1 for the black and white rhinos, respectively (Figure 3). The current location data shows that white rhinos appear to prefer a slightly cooler habitat as compared to black rhinos, which conforms to the finding that white rhinos avoid sun exposure during the hot period of the day (Owen-Smith 1973; Tichagwa et al. 2020). As the century progresses and the climate changes, the temperature conditions in all study parks will become increasingly unsuitable for both species, but it is predicted that white rhinos will be affected earlier than black rhinos (Figures S4–S8 in the Supplementary material). All the parks are showing drastic changes in the occurrence probability of rhinos, which is temperature dependent. All parks have areas with a probability of occurrence of 1 in the baseline scenario, which decreases to 0 under the high mitigation scenario, RCP 4.5, at mid-century.

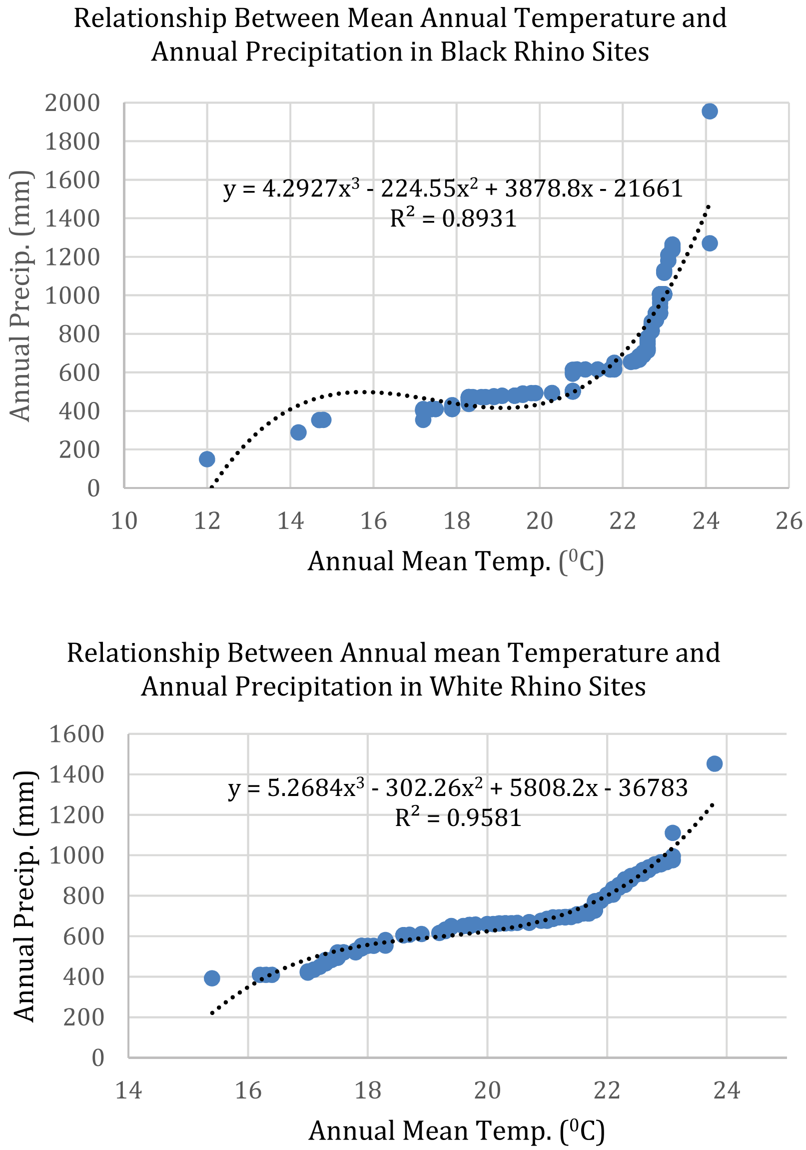


**Figure 2.** Relationship between annual mean temperature and annual precipitation in black and white rhinos observed in this study.

All parks have a 0 probability of occurrence for black and white rhinos under the business-as-usual scenario, RCP 8.5, by the late twenty-first century. Etosha and Hlane NPs are predicted to be the most affected by temperature changes. They have a probability of 0 for both species throughout their range under both RCPs late in the century. The effects of temperature changes are more pronounced on the white rhinos' probability of occurrence as the species shows more sensitivity to the projected temperature increases than the black rhinos. The effects of precipitation changes on the rhinoceros are much lower than those of temperature changes. But the study did find that the probability of black rhino occurrence is higher in the drier parts of the parks while white rhinos prefer the wetter parts of the parks.

## Discussion

The continued persistence of rhinoceros in the NPs in southern Africa will depend on many factors. In this study, we have modelled what the temperature and precipitation may be in the future under two IPCC climate scenarios. The trends that have emerged show that, not surprisingly, that temperatures will continue to increase as atmospheric $CO_2$ concentrations increase. All of the NPs examined in this study will see average temperatures increase by 2.2 ± 0.2°C by 2055 and 2.5 ± 0.3°C by 2085 under the 650 ppm (RCP 4.5 scenario). Under the 1370 ppm scenario (RCP 8.5), the average temperatures will increase by 2.8 ± 0.3°C by 2055 and 4.6 ± 0.6°C by 2085. These significant changes in average temperature will be challenging for the rhinoceros as they lack morphology to dissipate heat. Precipitation and water

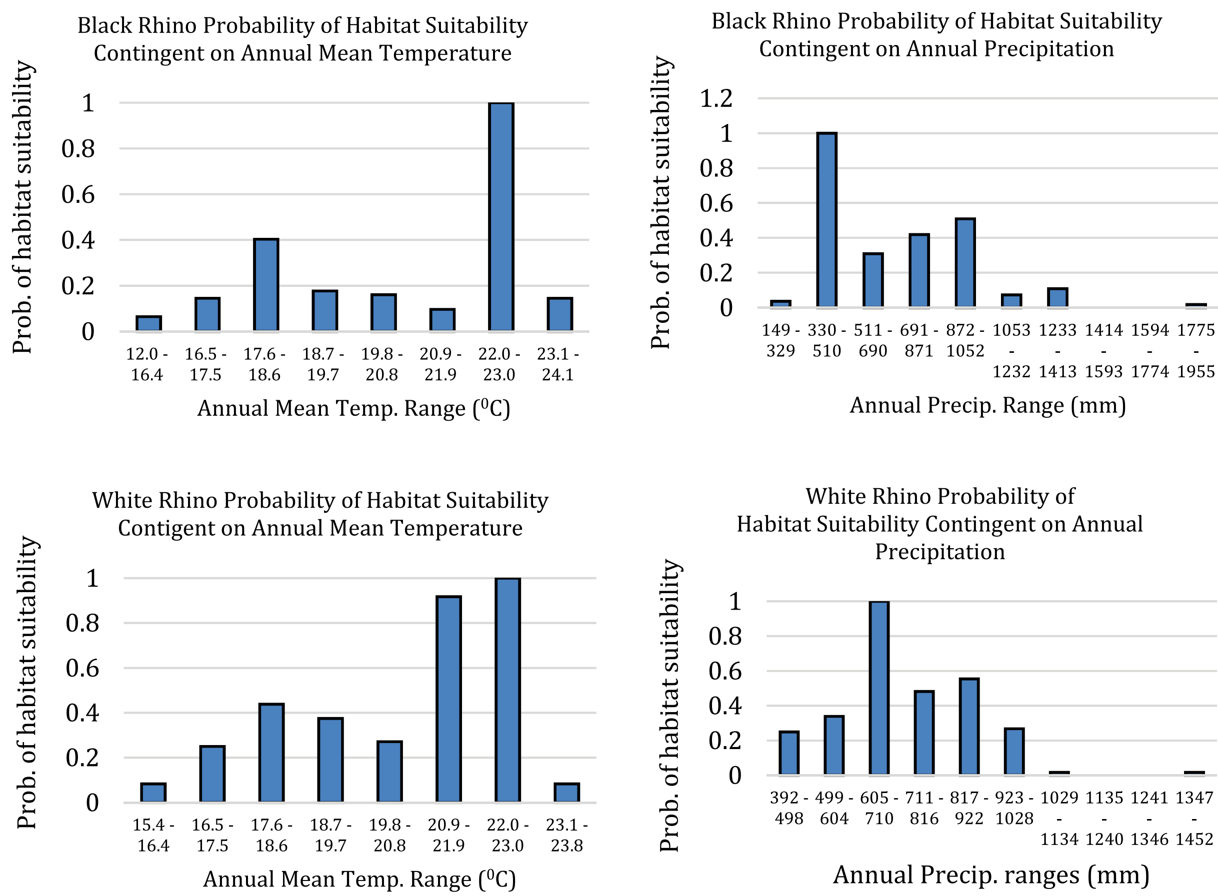


**Figure 3.** Rhino probabilities of habitat suitability contingent on annual mean temperature and annual precipitation.

availability can help the rhinoceros to handle high temperatures (Mitchell et al. 2018), but there are some areas that will see decreases in precipitation according to the model projections. For the black rhinos, the ideal mean annual temperature is between 17 and 22°C (Figure 3) with sufficient precipitation to support the growth of grasses, shrubs, and other forage. A previous study suggested that regions with less than 400 mm of precipitation per year were not conducive habitats for white rhinos (Pienaar 1994). All of the parks, except Tsavo West, will see decreases in precipitation under the future climate change scenarios; however, most of the parks will receive significantly more than 400 mm of precipitation. Therefore, even with the predicted decreases, there is little risk of precipitation becoming a limiting factor for the rhinoceros. The one exception is Etosha NP which may become too dry to support the rhinoceros.

With the influence of climate change, escaping high temperatures is an important behavioural response in white rhino (Rogers 2016). Many parks provide water to animals through artificial sources to mitigate the impacts of water scarcity. It should be noted that most of the parks considered are not developed for rhinoceros habitat but for biodiversity conservation, described as an uncoordinated set of game reserves and parks for recreational and economic interests (Crush 1980). For rhinoceros conservation to be effective, misting stations and wallowing mud pits may be required during peak temperature periods.

Our findings suggest that, as for many other species, climate change will profoundly impact the occurrence probability of both black and white rhinos in southern Africa. Many of southern Africa's arid and semiarid ecosystems are expected to become hotter and drier, with increased frequency and intensity of drought (Engelbrecht et al. 2015; Ferreira, le Roex, and Greaver 2019). The effects of increasing temperatures will be more pronounced than those of decreasing precipitation if the two variables are considered independently. Thus, management strategies should consider temperature and precipitation trends and variability, including extremes like maximum temperature and drought conditions. Surface water access has been shown to influence differences in space use by black rhinos in size and home range utilization (le Roex and Ferreira 2021; le Roex et al. 2019).

Changing climate influences black and white rhinos through impacts on population dynamics (Ferreira et al. 2015), animal survival (Maron et al. 2015), reduced conception rate (Shrader, Owen-Smith, and Ogutu 2006), and drought pressure on grasses available for rhinos (Vetter 2009). In addition, poaching continues to be a major threat to rhino populations (Shrader 2022). Since the physiological tolerances of black and white rhinos to the climatic variables are not well documented, and their plasticity is unknown, the predictions of the impacts of the changing climatic conditions on their occurrence likelihood may not be exact, but it should be recognized that conservation activities will be required to increase shadiness and access to water for the rhinoceros to thrive.

## Conclusion

As expected, the models have shown that climate change and associated temperature changes are likely to have significant impacts on habitat suitability for black and white rhinos on the Southern African continent. The modelled climate scenarios show that changes to precipitation will have a lesser effect on habitat suitability than the increase in temperature. The species' future depends on conservation strategies aimed at enabling habitat resilience which may include human intervention to modify landscapes. Considering that the Southern African continent houses approximately 89% of the remaining rhinoceros populations (Ferreira et al. 2022), what happens to the populations in this region will determine their persistence. The small sample used in this analysis is a limitation of this study, and further monitoring and research are needed to better understand the implications of climate change for rhinoceros populations.

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