Can climate change studies guide primate conservation in Africa? A systematic review of observed and projected impacts

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Abstract

Climate change is a growing threat, but its impact on species often remains poorly quantified which hampers conservation decisions. African primates are a conservation priority taxon, with 90% of species experiencing population decline. Yet, climate change impacts on this group remain comparatively understudied. We reviewed the peer-reviewed literature (n=58 studies, 2016-2025) to assess whether evidence on observed and projected impacts can guide conservation decisions. Observed studies (n=33) show that exposure to rising temperatures, changes in precipitation, and extreme events is well documented, and that weather variability affects fertility, survival, and stress in primates. However, only two studies focused on attribution and isolated climate change as a driver of these responses. Adaptive capacity is the least examined dimension of vulnerability, and no study quantified wildfire responses despite documented exposure. Projection studies (n=12) rely mainly on species distribution models, which estimate habitat suitability but not the mechanisms through which climate change affects populations. Current evidence can therefore identify exposed species and guide where climate-informed management is warranted, but rarely suffices to inform targeted interventions. Investment in infrastructure and capacity to conduct long-term monitoring and apply mechanistic methods is needed to attribute impacts to climate change and select specific conservation interventions.

Keywords: adaptive capacity, Africa, climate change impacts, evidence-based conservation planning, extreme climate events, impact attribution, primates, sensitivity, vulnerability

1 Introduction

Effective conservation planning depends on identifying which species are most vulnerable to environmental change, and through which mechanisms, so that limited resources for monitoring, habitat protection, or direct intervention can be prioritized accordingly. Climate change is one such driver of vulnerability (Jaureguiberry *et al* 2022), but its consequences often remain too poorly quantified to guide conservation decisions (Thomas *et al* 2026). Climate change can threaten species through multiple mechanisms, including increasing physiological stress from rising temperatures (Murali *et al* 2023), degradation of food resources (Bush *et al* 2020), shifts in suitable habitat (Brodie *et al* 2025), and increased exposure and sensitivity to pathogens (Lucore *et al* 2024, Thomassen *et al* 2013). Importantly, this is not limited to gradual shifts in mean temperature and rainfall, but species will be increasingly exposed to extreme climate events that can exacerbate other threats such as habitat loss or diseases (Heinicke *et al* 2026).

Understanding climate change driven vulnerability is especially needed across Africa, where despite its high biodiversity, climate change impact research remains comparatively scarce (White *et al* 2021, Overland *et al* 2022). In Africa, the last decade was the warmest ever recorded (WMO 2025), and extreme rainfall, drought, heatwaves, tropical cyclones and wildfires are projected to increase across African regions (Heinicke *et al* 2026, Kropf *et al* 2025, Dosio *et al* 2021). Changes in climate and extreme events can have particularly strong impacts on tropical biodiversity, because tropical climates have historically varied little and are projected to be the first exposed to unprecedented climatic conditions (Mora *et al* 2013, Schuhen *et al* 2026).

Though primates are a conservation flagship species and a focus of research activities, they are strongly understudied in terms of climate change impacts compared to other taxa, such as birds, amphibians, or temperate mammals (Bernard and Marshall 2020). Across Africa, there are 213 primate species, the majority of which are classified as 'Threatened' by the IUCN Red List of Threatened Species and 90% having declining populations (IUCN 2025). Main threats to African primates include habitat loss and degradation, hunting and diseases (Estrada *et al* 2017). Primates are especially vulnerable to climate change, due to their dependence on specific habitats and food sources, slow reproductive rate and limited dispersal ability (Korstjens and Hillyer 2016, Zhang *et al* 2019).

There are two broad types of studies of climate change impacts and they inform different aspects of conservation practice. Future suitability projections, often based on species distribution models (SDM, i.e., statistical models that relate species' occurrence to environmental predictors to estimate habitat suitability), identify where suitable habitat may persist or emerge and thereby help prioritize areas for protection. Their outputs depend on assumptions of species dispersal ability, and the climate models and scenarios chosen (Pacifici *et al* 2015). Where scenarios vary climate and land-use separately, projections can also estimate how much each driver contributes to future change in habitat (Hari *et al*

2026). In contrast, studies of observed change can quantify the drivers of change that has already occurred and can show whether and through which mechanisms climate change contributes to population changes. This evidence is required to justify climate-targeted conservation interventions (Caro et al 2022, Thomas et al 2026). For African primates, it is unclear which of these evidence types is available.

Previous reviews of climate change impacts on primates have provided qualitative descriptions of different mechanisms through which climate change can affect primate populations (Korstjens and Hillyer 2016), and an assessment of how research effort is distributed across primate taxa and regions, and which variables have been studied (primates, their habitats, or their food, Bernard and Marshall 2020). Here, we systematically reviewed the peer-reviewed literature on climate change impacts on African primates published over the past ten years (2016-2025) since the publication of the qualitative review by Korstjens and Hillyer (2016). We assess what is known about primate vulnerability to climate change, defined by exposure, sensitivity and adaptive capacity (Foden *et al* 2019), and how well this evidence can support conservation decisions. Specifically, we ask: (1) which dimensions of vulnerability to climate change have been studied, (2) to what extent studies have examined observed versus projected future impacts, and (3) which species response variables and climatic variables have been investigated. Based on this, we identify evidence gaps and derive recommendations for best practices for climate data use and reporting, intended to help both conservation practitioners judge the reliability of existing evidence and researchers assessing climate vulnerability in primates or other taxa.

2 Methods

2.1 Review scope and eligibility criteria

This review focuses on peer-reviewed studies that examine the impacts of climate change on free-living primates in Africa, including monkeys (Cercopithecoidea), apes (Hominidae), and strepsirrhines (Strepsirrhini). We focused our review on studies published between 2016 and 2025, to focus on evaluating recent progress and emerging trends over the past decade. To be included, studies had to directly assess at least one dimension of vulnerability to climate change, covering either observed or projected impacts.

We define species vulnerability to climate change along three dimensions: exposure, sensitivity and adaptive capacity (Foden *et al* 2019). Exposure refers to the magnitude of climatic change experienced by a species (or population), for example, temperature increases or extreme climatic events occurring in areas where species occur. Sensitivity describes to which degree a species is negatively affected by climatic changes, for example, through reduced fertility or survival. Species traits, such as the dietary specialization, are also used to assess species sensitivity. Adaptive capacity captures a species' ability to react to negative impacts, for example, by avoiding affected areas, resting more when temperatures are high or through thermoregulatory behavior. For sensitivity, we further differentiate whether a study investigates species' sensitivity to weather variability, or formally attributes an

observed change to climate change (O'Neill *et al* 2022). Specifically, formal attribution is defined as isolating the effect of climate change on a biological response from other non-climatic drivers (Thomas *et al* 2026). Studies on species sensitivity to weather variability were considered, as responses to short-term climatic fluctuations can be informative for conservation decisions where formal climate change attribution studies are lacking.

Studies assessing the impact of climate change on habitat, food availability, or parasites and pathogens were included when the study made a direct connection to primate populations. We also included review articles meeting our criteria. Studies were excluded if they did not explicitly analyze climate change impacts, or if primates were not specifically addressed as a focal taxon (e.g., broader studies on land vertebrates or mammals).

2.2 Literature search and screening

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to systematically identify and screen relevant literature (Page *et al* 2021). A literature search was conducted in Scopus (www.scopus.com) and Web of Science (www.webofscience.com) using search terms related to climate change, primate taxa, and Africa, combined using the Boolean operators "AND" and "OR" (Table 1). We excluded grey literature to ensure that all studies had undergone formal peer review as an indicator of baseline methodological rigor. We also excluded non-English publications, which is likely to lead to an underrepresentation of localized literature, but ensures a consistent baseline, and maintains comparability across studies.

The initial search yielded 133 unique studies, which were subsequently screened in full against the eligibility criteria described above. This process resulted in a final set of 58 peer-reviewed articles included in the systematic review (Supplementary table S1). The number of studies excluded at each step and the reasons for exclusion are summarized in Figure 1.

Each of the 58 included studies was classified by study type: direct impact studies (investigating climate change impacts on primates directly), reviews of published literature, or indirect impact studies (investigating climate change impacts on primate habitat, food resources, or pathogens without directly assessing consequences for primates). More detailed information was not extracted from indirect impact studies (beyond the spatial and taxonomic scope), as the downstream effects of climate change on primates were not addressed within those studies themselves. Similarly, for reviews, further information extraction was not applicable as these studies cover a wide range of primary literature, and consequently span multiple time periods, and methods.

For direct impact studies, information was extracted on the time period type (observed impacts, paleoclimatic, or future projection) and the dimension of vulnerability assessed (i.e., exposure, sensitivity, adaptive capacity). For studies that assessed observed species sensitivity, we additionally distinguished whether the study attributed impacts to climate change or investigated species' sensitivity to weather variability.

Across all direct impact studies, we further extracted the time period covered, the response variable (e.g., species' geographic range, occurrence, traits, or behavior), the climatic variable investigated (e.g., temperature, precipitation, or type of extreme event), and the source of climatic data (text box

1 and 2). For studies using simulated data, we recorded the climate models used. For simulated future studies, we additionally noted the emissions scenario (Representative Concentration Pathways (RCP), Shared Socioeconomic Pathways (SSP)). For all studies, we recorded the spatial scope, taxonomic scope, and the method used to assess the relationship between the climatic predictor and the response variable. All analyses were implemented in R 4.5.1 (R Core Team 2025).

3 Results

3.1 Overview

Of the 58 studies, 44 (76%) investigated the direct impact of climate change on African primates, nine (16%) were literature reviews, and five (7%) analyzed indirect impacts. The review studies covered either broad topics, such as threats to primates (Estrada *et al* 2017), environmental stress (Kamilar and Beaudrot 2018), climate change impacts on primates (Korstjens and Hillyer 2016), and taxonomic and spatial gaps in climate change research (Bernard and Marshall 2020), or more specific topics, including torpor and hibernation (Blanco *et al* 2018), the modelling of climate change impacts (Winder *et al* 2023), and a single species review (*Galago moholi*, Scheun and Nowack 2024). The five indirect studies focused on climate change impacts on forests where primates occur (Babweteera *et al* 2018, Chapman *et al* 2021), changes in fruit availability (Federman *et al* 2017), and pathogens, including malaria (Liu *et al* 2017) and parasites (Bonnell *et al* 2016).

The paleoclimate studies addressed questions of climatological suitability of areas and climate refugia. Rowan et al. (2016) additionally examined whether paleoclimate explains primate community structure. Three studies extended back to the Last Glacial Maximum (22,000 years BP) and one to the Last Interglacial (120,000 years BP).

Of the 44 direct studies, and with respect to the three dimensions of species vulnerability, 21 studies investigated species exposure, 22 species sensitivity, and seven adaptive capacity (Figure 2). Of those, four studies investigated two dimensions, and one study investigated all three dimensions (Zhang *et al* 2019). In terms of temporal scope, 33 studies covered an observed time frame (i.e., recent past), 12 used future projections, and four simulated paleoclimate conditions. Three studies covered two of these scopes and one study covered all three (Supplementary table S1).

The reviewed studies also show spatial and taxonomic biases, though these were already reviewed in more detail elsewhere (Bernard and Marshall 2020). Spatially, Madagascar was the most studied region (15 of 44 direct studies). Five studies were located in eastern Africa, four in southern Africa, three in western Africa, and none in Central Africa. The remaining either had a global or Africa-wide scope (details Supplementary table 1). Taxonomically, lemurs were the most studied group (16 studies), followed by apes (eight studies), baboons and geladas (together seven studies).

3.2 Observed climate change impacts on African primates

Of the 33 observed studies, only two explicitly aimed to attribute observed responses to climate change (Ozgul *et al* 2023, Campos *et al* 2017). The remaining studies examined sensitivity to weather variability. The two attribution studies spanned 25 and 29-52 years (respectively), whereas eleven

observed studies covered only one or two years. The most common response variables were species ranges or presence data (13 studies), followed by behavior (e.g., activity budgets, thermoregulatory behavior, nine studies) and physiological, hormonal or morphological responses (nine studies). Only three observed studies examined demographic parameters such as fertility and mortality, and two used species traits. Three studies examined more than one response variable (Ameca *et al* 2023, Zhang *et al* 2019, Young *et al* 2019).

Across the 33 observed studies, temperature was the most comprehensively studied climatic variable across all three vulnerability dimensions (26 studies, 79% of studies, Table 2). In terms of exposure, African ape sites and primate ranges more broadly have been shown to experience temperature increases (Kiribou *et al* 2024, Yang *et al* 2025). Species sensitivity to temperature has been studied across multiple response variables. At the demographic level, higher temperatures are associated with reduced fertility in blue monkeys (*Cercopithecus mitis*, Campos *et al* 2017) and lower survival in grey mouse lemurs (*Microcebus murinus*, Ozgul *et al* 2023). Behaviorally, samango monkeys (*Cercopithecus albogularis*) adjust time spent feeding in response to temperature variation (Coleman *et al* 2021). Physiologically, geladas (*Theropithecus gelada*) and samango monkeys show elevated glucocorticoid levels under cold stress (Tinsley Johnson *et al* 2018, LaBarge *et al* 2022), sportive lemurs (*Lepilemur leucopus*) exhibit higher metabolic rates during the cool, dry season (Bethge *et al* 2017), and chimpanzees (*Pan troglodytes*) living in hot environments have elevated cortisol levels suggesting heat stress (Wessling *et al* 2018b). Importantly, mean temperature is among the strongest predictors of lemur extinction risk (Brandon *et al* 2024). Evidence on adaptive capacity to temperature change is limited, but it has been shown that mountain gorillas (*Gorilla beringei beringei*) and Verreaux's sifakas (*Propithecus verreauxi*) show thermoregulatory behaviors in response to high temperatures such as increased drinking and tree-hugging (Wright *et al* 2022, Chen-Kraus *et al* 2023).

Precipitation change (22 studies, 67 %) and drought (5 studies, 15 %) are the second most studied climatic variables. Exposure to drought has been documented across multiple species, specifically vervet monkeys (*Chlorocebus pygerythrus*, Young *et al* 2019), ring-tailed lemurs (*Lemur catta*, Fardi *et al* 2018), and Verreaux's sifaka (Veilleux *et al* 2024), as well as across primate ranges globally (Yang *et al* 2025). Sensitivity is evident across all response variable categories. Droughts increase mortality in vervet monkeys (Young *et al* 2019), and reduce fertility in sifakas and blue monkeys (Campos *et al* 2017). Lower survival is also documented in grey mouse lemurs under reduced rainfall (Ozgul *et al* 2023). Behaviorally, vervet monkeys, sportive lemurs, and bamboo lemurs (*Prolemur simus*) all shift activity budgets in response to drought or reduced rainfall (details in Table 2, Young *et al* 2019, Mandl *et al* 2018, Eronen *et al* 2017). Physiological stress responses (measured through creatinine, glucocorticoids, cortisol, and metabolic rate) are consistently elevated under drought or low-rainfall conditions across multiple species (Young *et al* 2019, Fardi *et al* 2018, Bethge *et al* 2017, LaBarge *et al* 2022, Wessling *et al* 2018b, 2018a, details in Table 2). However, evidence on adaptive capacity to precipitation change is sparse. A global vulnerability assessment estimated that 22% of all primate taxa are vulnerable to drought when accounting for both sensitivity and adaptive capacity (Zhang *et al* 2019), but we found no species-level assessments among the studies reviewed.

In contrast to temperature and precipitation (including drought), evidence on the impacts of other extreme climate events is largely restricted to exposure. Five studies investigated tropical cyclones, two flooding and one study included wildfire and landslides. Global assessments show that African primates are exposed to all of these hazards (Yang *et al* 2025, Ameca *et al* 2023), and landslides represent the most prevalent hazard (Yang *et al* 2025). Global studies estimated that 16% of all primate taxa are vulnerable to tropical cyclones because of high sensitivity and low adaptive capacity (Zhang *et al* 2019), while 60% of primates have been assessed as having low capacity to adapt to tropical cyclones (Ameca *et al* 2023). A study on ring-tailed lemurs showed elevated hair cortisol and reduced body weight after tropical cyclones (Fardi *et al* 2018). For flooding, one study documented shifts in spatial distribution and relative abundance of chacma baboons (*Papio ursinus*) and vervet monkeys following cyclone-induced flooding (Beardmore-Herd *et al* 2025). Notably, though primates are exposed to wildfires (Yang *et al* 2025, Harrison *et al* 2026), none of the studies reviewed investigated primates' sensitivity or adaptive capacity to wildfires in the context of climate change.

3.3 Projected climate change impacts on African primates

Of the 12 future studies, six studies used species distribution models, four investigated spatial overlap and two used phylogenetic models. Three studies relied on a single climate model (GCM), one used two GCMs (one per scenario), and the remaining studies used between three and 18 GCMs. Four studies did not specify which GCMs were used. Nine studies used at least two climate scenarios, one study calculated the average across two scenarios and one did not specify the scenario used.

Across the studies, temperature was again the most comprehensively studied climatic variable (11 studies). In terms of exposure, temperatures are projected to increase across all African ape sites under both low- and medium-high emission scenarios (RCP2.6 and RCP6.0, Kiribou *et al* 2024), and across primate ranges globally, temperatures are projected to increase by 10% more than the global mean (scenario not specified, Graham *et al* 2016). Under a 2°C global warming scenario, temperature for 26.1% of all primate ranges is projected to be above pre-industrial conditions (Stewart et al 2020). Under a high-emission scenario (RCP8.5), 86% of primate ranges globally are projected to be exposed to temperature increases of more than 3°C (Carvalho *et al* 2019). The same study projects widespread loss of primary habitat especially across Africa, affecting 95% of African forest primates (Carvalho *et al* 2019). Evidence on adaptive capacity to temperature change suggests that rates of niche evolution in primates globally are considerably lower than the pace of projected temperature-related climate niche evolution (Meyer and Pie 2022). Similarly, Brandon et al. (2024) show that traits in lemurs are unlikely to evolve fast enough to track changes in climatic conditions across Madagascar.

Projected changes in precipitation are heterogeneous across African primate ranges. Exposure to increased drought is nevertheless expected to be widespread. Specifically, some African ape sites are projected to experience up to 20 additional consecutive dry days per year, with the largest increases estimated for eastern gorilla sites (Kiribou *et al* 2024). For the bamboo lemur, a lengthening of the dry season comparable to conditions at sites where the species is now extinct, is projected for many populations (Eronen *et al* 2017). The increase in seasonality may exceed the capacity of this dietary

specialist to persist (Eronen *et al* 2017). As for temperature, niche evolution in primates globally is much slower than the pace in projected precipitation changes (Meyer and Pie 2022).

Several studies projected changes in suitable habitat or geographic range, mostly based on temperature and precipitation change, and mostly project a strong decline. For African apes, Carvalho et al. (2021) paired a best-case climate scenario (RCP4.5) with a best-case land-use scenario, and a worst-case climate scenario (RCP8.5) with a worst-case land-use scenario, and compared the two combinations. Assuming African apes do not disperse, an average range decline of 50% outside protected areas is projected, rising to 94% across study regions under the worst-case scenario (Carvalho *et al* 2021). For geladas, models project a 36% reduction in suitable habitat by 2050 and a 52% reduction by 2070 (averaged across different emission scenarios), with losses concentrated south of the Rift Valley (Ahmed *et al* 2023). Impacts on baboons (genus *Papio*) are projected to be more variable. Specifically, for chacma (*P. ursinus*) and Kinda baboons (*P. kindae*) suitable habitat is projected to decline substantially by 2070 (RCP2.6 and RCP6.0), whereas suitable habitat is projected to increase for olive (*P. anubis*) and hamadryas baboons (*P. hamadryas*, Hill and Winder 2019). Both the genera *Cercopithecus* and *Colobus* are predicted to lose suitable sites, with losses concentrated in West Africa, while central African regions are expected to retain the largest areas of climatically suitable habitat, though in increasingly fragmented form (Korstjens 2019). For ruffed lemurs (genus *Varecia*), Morelli et al. (2020) built a deforestation model for eastern Madagascar and ran climate-only, deforestation-only and combined projections. They projected climate change to reduce suitable habitat by 14-75% by 2070 under a high-emission scenario (RCP8.5), rising to 38-93% when combined with ongoing deforestation (Morelli *et al* 2020). Notably, even if protected areas prevent further deforestation, climate change is still projected to reduce suitable habitat by 38-83% (Morelli *et al* 2020).

In contrast to temperature and precipitation, only one of the 12 projection studies included data on extreme climate events (Kiribou *et al* 2024), covering only African apes. Therein, all African ape sites are projected to be frequently exposed to wildfires and crop failures, with 84% of sites projected to experience heatwaves and 78% to be exposed to river floods (Kiribou *et al* 2024). Tropical cyclones and droughts are projected to increase in frequency only for some sites in western and central Africa (Kiribou et al 2024).

4 Discussion

We identify four main findings from this review. First, we found that exposure and sensitivity are the most studied dimensions of primate vulnerability to climate change, with far less studies focusing on adaptive capacity. Second, evidence on impacts of extreme climate events is markedly sparser than on temperature and precipitation impacts. Third, only two studies implemented an impact attribution approach, which illustrates that we know surprisingly little on how climate change is already impacting African primates. Fourth, we found a strong variation in reporting completeness on types of data used.

4.1 Dimension of vulnerability studied for African primates

First, it needs to be highlighted, that although this was not the objective of this study, the conclusion by Bernard & Marshall (2020) that climate change impacts on primates are understudied compared to other taxa, still holds given that we found that the number of studies remains constant over the years (two to eight studies per year). Exposure is relatively well-studied, also across different types of extreme events. However, for extreme events, sensitivity and adaptive capacity are almost entirely unassessed. This gap is particularly concerning as, for example, wildfires are expanding into new habitats where they have historically not occurred, such as cool and moist mountainous areas in Central Africa (Mason *et al* 2026). For sensitivity to climatic changes, behavioral and physiological responses are increasingly documented, yet the link from these responses to population-level consequences (i.e. demography) remains limited. This demographic gap (e.g., limited data on fertility and mortality responses) is an important limitation, because demographic rates underpin extinction risk assessments and are needed to assess population viability under climate change (Paniw *et al* 2021). Understanding such mechanisms also guides which conservation interventions are needed. For example, chimpanzees in arid regions compete with humans and livestock over water sources, and understanding this mechanism informed a recent intervention in Senegal, where additional water holes were created for livestock so that natural water holes remain available to chimpanzees.

4.2 Attributing observed impacts to climate change

Attribution studies were the least represented evidence type in our review (two studies, compared with 12 projection studies). Although conceptually similar to projection studies, attribution studies differ because they focus on historical, observed drivers. Projections estimate how future climate change could affect species, but they rely on assumed relationships between climate and species responses and include scenario uncertainties. Without attribution, we do not know whether these relationships hold in existing populations already exposed to climate change, or whether climate change is a relevant driver compared to habitat loss and hunting. Such evidence is also relevant beyond conservation management, because climate loss and damage funding and legal claims for compensation of climate-related losses both require causal evidence that links the observed impacts to climate change (Roe *et al* 2023, Stuart-Smith *et al* 2021). Thomas et al. (2026) recently reviewed in detail the range of causal approaches available for biodiversity change attribution, covering observational inference, experiments, and process-based modelling. The two studies in our review that explicitly aimed at attribution illustrate two such approaches.

Ozgul et al. (2023) qualifies as a retrospective process-based attribution study. It first linked observed climate variables to population demographic rates. Then they implemented a process-based demographic model that turned demographic rates into an explicit function of environmental conditions and population density. By comparing projections under early versus recent climate conditions, they attributed the observed increase in life-history speed and population instability to observed changes in temperature and rainfall.

Campos et al. (2017) likewise aimed to attribute vital rate variation to climate change. They used a statistical approach and correlated interannual variation in vital rates with interannual variation in

climate variables. The use of long-term data (29-52 years) distinguishes this study from the shorter weather-sensitivity studies in our review. However, the approach included only climate predictors without accounting for other potential drivers (e.g., population density, habitat change), and no explicit counterfactual baseline was constructed against which the observed vital rates could be compared. Incorporating such covariates in future studies would strengthen confidence in attribution attempts using this type of long-term demographic data (Thomas *et al* 2026).

The IPCC defines impact attribution as comparing the observed state of a system (for example, population size or the area of suitable habitat) under factual conditions (i.e., with climate change) to its state under counterfactual conditions (i.e., without climate change) (O'Neill *et al* 2022). This approach remains underutilized in biodiversity research and has not yet been applied to primates. An example of how impact attribution can be implemented using counterfactual climate data is a recent study on bumblebees in Europe (De Tandt *et al* 2026). In that study, species distribution models were trained on observed climate data and then projected under observed climate and counterfactual climate data from which long-term climate trends had been removed (Frieler *et al* 2024). The difference between both projections was attributed to climate change. Both the factual and counterfactual climate datasets used are openly available through the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, www.isimip.org, details in Frieler *et al* 2024).

Long-term study sites with multi-decadal monitoring records hold the type of data needed for attribution studies. The combination of time series long enough for climate change attribution and existing demographic monitoring makes them uniquely suited to advance our understanding of how climate change affects primate population dynamics. Practitioners can therefore only treat the sensitivity patterns reported here as indicating where primates may be vulnerable.

4.3 Moving beyond species distribution models

SDMs dominate the projection studies reviewed here. However, they have known limitations for representing mechanisms of impact (Serra-Diaz and Franklin 2019). They describe correlative relationships between climate and occurrence but do not capture physiological constraints, behavioral plasticity, or demographic processes. Process-based alternatives can identify the mechanisms behind species-environment relationships and use those relationships to predict how species may respond to environmental changes. Example of process-based primate models include time-budget models (Korstjens *et al* 2018, Dunbar *et al* 2019), life-cycle models (Ozgul *et al* 2023), biophysical models (Slater 2021, Stalenberg 2019, Kearney and Porter 2009, Zhang *et al* 2025), individual or agent-based models (van Leeuwen 2019, Imong *et al* 2016, Robbins and Robbins 2004). Such mechanistic understanding is especially needed as climate change is pushing ecological systems into environmental conditions outside the range of historical observations, where models trained solely on past data may no longer reliably predict biological responses. Process-based models can also help to identify the pathway through which climate affects a population, for example, heat stress reducing fertility or water scarcity reducing survival. This identifies the point at which a conservation intervention can act, such as securing water sources or protecting thermal refugia.

4.4 Best practices for climate data use and reporting

Consistent reporting of climate data is a prerequisite for contextualizing findings and comparing them across studies. At a minimum, studies should explicitly report the time period and temporal resolution of climate data used, the GCMs and CMIP generation from which data were drawn, and the emissions scenario (e.g. SSP- RCP, text box 1 and 2). Our review reveals that this standard is not consistently met.

Although this may appear to be a technical detail, the choice and number of GCMs has direct implications for how well studies capture uncertainty in future projections. Studies should use multiple GCMs that span the full range of projected conditions (Schoeman *et al* 2023), including models with higher equilibrium climate sensitivity (ECS is a metric that quantifies how strong global temperatures increase with a doubling of atmospheric CO_2 concentration). Systematically excluding models that project stronger warming, what has been termed 'hot models', from analyses of climate change impacts could result in the underestimation of regional climate impacts (Swaminathan *et al* 2024). Ideally, results are reported both per model and as a multi-model ensemble. In our review, three projected studies used a single GCM, which precludes any assessment of climate model uncertainty. As GCMs are continuously being developed and updated, studies should draw on the most recent CMIP round available to ensure projections reflect the latest model improvements (details Text box 2). Making this uncertainty explicit matters for conservation decisions, because when projections from multiple GCMs converge on the same direction of change, conservation action can be prioritized with greater confidence. However, when projections diverge, the uncertainty should be assessed further (e.g., by examining the drivers of model disagreement) before committing resources to conservation interventions.

Scenario choice is a further consideration. SSP5-8.5 (RCP8.5) is now widely regarded as a low-probability counterfactual rather than a policy-relevant outcome (Schoeman *et al* 2026). Current emission trajectories are projected to lead to 2.8°C warming by 2100, and even full implementation of the Nationally Determined Contributions would still result in 2.6°C (UNEP 2026). These projections fall between the scenarios SSP2-4.5 and SSP3-7.0. For studies aiming to inform conservation planning, scenarios approximating the Paris Agreement (SSP1-2.6) are relevant as a mitigation benchmark. In addition, reporting results across a range of scenarios rather than a single extreme case better represents the uncertainty decision-makers need to weigh (Schoeman *et al* 2026). For the next phase of the Climate Model Intercomparison Project, CMIP7, a new set of scenarios has been defined (Van Vuuren *et al* 2026). They comprise seven scenarios ranging from 'Very low' to 'High' and are not designed to match specific CMIP6 scenarios. As climate model output for these scenarios is released, studies should state clearly which scenario generation was used, so that results remain comparable across studies.

4.5 Limitations

Our search was restricted to English-language, peer-reviewed literature, following standard systematic review practice for reproducibility (Page *et al* 2021). This restriction likely underrepresents regionally-specific studies published outside academic journals, such as technical reports or French-

language sources relevant to francophone states. A larger search might plausibly reveal more weather-sensitivity or exposure studies. However, it is unlikely to substantially change our central findings, since technical reports rarely apply the long-term, counterfactual-based designs required for attribution, nor is it likely to employ novel modelling approaches beyond species distribution models.

5 Conclusion

For researcher, this review identifies several directions for future research. Most urgently, the field needs more studies that explicitly attribute observed responses to climate change rather than inferring sensitivity from weather variability alone. This is a significant gap given the threatened conservation status of many African primate species and their documented sensitivity to climate variability. More specifically, analyses linking climate variables to behavioral, demographic or physiological responses are needed to understand the mechanisms of species' vulnerability to climate change. This can not only support population viability assessments, but also guide decisions on which type of conservation interventions are needed. As exposure to extreme climate events and to multiple event types is projected to increase, research on primates' sensitivity and adaptive capacity to such events becomes increasingly urgent, given that vulnerability is currently assessed almost exclusively through exposure.

For conservation practitioners and funders, in the absence of attribution studies for most species, the sensitivity patterns identified in this review (Section 3.2) can serve as an interim basis for identifying which populations warrant closer monitoring or climate-informed management. Funders should invest in long-term research, including the infrastructure and analytical capacity needed to collect, manage, and analyze multi-decadal datasets, as these are a prerequisite for impact attribution.

Text boxes

Text box 1. Overview of types of climate data sources for the observed period.

In-situ measurements

Many studies reviewed here use data recorded at local weather stations, data loggers or rain gauges at field sites (18 studies corresponding to 41% of direct studies). While data loggers provide high temporal resolution at the precise location of observation, they typically cover only the duration of the study period. Weather stations operated by national meteorological services can also serve as a data source, though spatial coverage across Africa is limited, there are different initiatives to counteract this trend (Dinku 2019). The Trans-African Hydro-Meteorological Observatory (TAHMO) aims to complement these efforts by installing cost-effective weather stations at a high spatial coverage across sub-Saharan Africa (van de Giesen *et al* 2014) with data available at https://tahmo.org/climate-data/. However, these data are not available over longer periods yet and thus are likely not suitable for attribution studies.

CRU TS provides a global gridded dataset of monthly climatic variables at 0.5° resolution (around 50km) from 1901 onwards, derived by interpolating station observations (Harris *et al* 2020). WorldClim offers an alternative gridded product at higher spatial resolution (30 arcseconds,

approximately 1 km) covering 1970–2000, also based on interpolated station data (Fick and Hijmans 2017). Kearney et al. (2020) developed an approach using existing R packages to derive microclimatic variables from gridded historical data at hourly resolution and 30 m spatial resolution, that can be used to analyze species responses to changes in microclimate.

It is worth noting that higher spatial resolution does not necessarily imply higher data quality, because gridded products derived by interpolating sparse station networks may carry substantial uncertainty in regions where station coverage is very low (Tarek *et al* 2021). Higher spatial resolution adds value only if it draws on additional data sources to compensate for sparse station coverage.

Reanalysis data

Reanalysis products combine observational data with model simulations. They have the advantage of being physically consistent across variables and space, as they are produced by a single model framework constrained by available observations, rather than relying on spatial interpolation between measurement points (Hersbach *et al* 2020). ERA5, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), provides global data since 1940 at 0.25° resolution (~ 25 km) with hourly temporal resolution (Hersbach *et al* 2020). Over land, ERA5-Land provides data at 9 km resolution since 1950. ISIMIP provides four reanalysis climate datasets (GSWP3-W5E5, 20CRv3-W5E5, 20CRv3-ERA5, 20CRv3) all at 0.5° resolution and daily temporal resolution covering 1901–2019 (Frieler *et al* 2024). This allows to include uncertainty from climate data in an analysis and ISIMIP also provides counterfactual climate data for the same datasets. In addition, ISIMIP provides CHELSA-W5E5 at 30 arcseconds (~ 1 km) and daily resolution for 1979 to 2016 (Karger *et al* 2023).

Satellite-derived data

Many different satellite-derived data products exist and we here mention some as examples. For precipitation, the Tropical Rainfall Measuring Mission (TRMM) provides data from 1998-2015 at approximately 25 km resolution, and its successor, the Global Precipitation Measurement (GPM) mission, extends coverage from 2014 to the present at sub-daily temporal and 10 km spatial resolution (NASA, https://gpm.nasa.gov/). CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) combines satellite data with station observations to provide daily precipitation from 1981 onwards at 0.05° spatial and sub-daily temporal resolution (Funk *et al* 2015).

For land surface temperature, MOD11 is based on MODIS data and provides daily data at 0.01° resolution (~1 km) from 2000 onward (Wan *et al* 2015). The Copernicus land surface temperature dataset provides monthly data at 0.01° resolution from 1995 onwards, derived from multiple satellite products (Ghent *et al* 2025)

Extreme event data

Several datasets compile observed extreme events. Both Zhang et al. (2019) and Yang et al. (2025) list data sources covering tropical cyclones, droughts, landslides, flooded area and wildfires. The Emergency Events Database (EM-DAT) records disaster occurrence, affected (human) populations, and economic damages worldwide (EM-DAT, CRED 2020). Observed temperature and precipitation

extremes indices are, for example, compiled in HadEX3, a global gridded dataset at 1.25° × 1.875° resolution covering 1901–2018 at monthly resolution (Dunn *et al* 2020).

Text box 2. Overview of types of climate data sources for the future period.

For a detailed guide on using climate model output in ecological research, we refer readers to Schoeman et al. (2023).

General Circulation Models

General Circulation Models (GCMs) simulate the physical processes of the climate system, including the atmosphere, ocean, land surface, and sea ice. Earth System Models (ESMs) extend this framework by additionally representing biogeochemical cycles, such as the carbon cycle and vegetation dynamics, allowing for feedbacks between the physical climate and the biosphere. Both produce historical simulations and projections of future climate under different emissions scenarios, typically at a spatial resolution of 100-250 km. GCM output is publicly available through the Earth System Grid Federation (ESGF, details in Schoeman et al. (2023)).

CMIP and emissions scenarios

GCM simulations and outputs are coordinated through the Coupled Model Intercomparison Project (CMIP), which provides a standardized framework for running and comparing models across research groups worldwide. Successive CMIP generations (CMIP5, CMIP6 and now CMIP7) reflect improvements in model structure, resolution, and process representation, and using the most recent generation is generally preferable. Future projections are run under defined emissions scenarios, called Representative Concentration Pathways (RCPs) in CMIP5, and Shared Socioeconomic Pathways (SSPs) in CMIP6. These scenarios span a range of plausible futures from strong mitigation to high emissions. CMIP7 introduces a new set of seven scenarios, from very low to high emissions, and output from GCMs based on these new scenarios is starting to become publicly available.

Regional climate models

Regional Climate Models (RCMs) dynamically downscale GCM or ESM output to finer spatial resolutions, typically 10-50 km, by solving the physical equations of the climate system at higher resolution over a limited domain. Unlike statistical downscaling approaches used in preprocessed products (see below), RCMs can introduce regional physical processes that are not resolved in the driving GCM. The Coordinated Regional Climate Downscaling Experiment (CORDEX) provides a standardized framework for RCM simulations across multiple continental domains, including Africa (CORDEX-Africa). For studies in regions with complex topography or strong regional climate signals, RCM output from CORDEX may therefore provide more physically meaningful spatial detail than preprocessed products.

Preprocessed data products

Climate data products from WorldClim or ISIMIP are preprocessed derivatives of GCM output. They have been bias-corrected and downscaled to finer spatial resolutions to make them more accessible for studying climate change impacts. However, downscaling does not introduce physical processes that are absent from the underlying GCM. WorldClim provides data as multi-decadal climatological averages (e.g., monthly average temperature for 2061-2080 as a single value per grid cell) for 23 GCMs at a spatial resolution of up to 30 arc-seconds (~1 km, Fick and Hijmans 2017). In contrast, ISIMIP provides data at high temporal resolution (daily time series) for five GCMs though at lower spatial resolution (0.5°, ~ 50 km, Frieler *et al* 2026).

Choosing climate models

With more than 50 models available in CMIP6, selecting appropriate models for a given study region is non-trivial. Tools such as ESMValTool (Eyring *et al* 2020) allow researchers to evaluate model performance against observed climate data, and can help identify models that best reproduce current conditions in a region of interest. However, good performance under present-day conditions does not guarantee that a model best captures the processes relevant for future climate, particularly as projections move further from the observed record. Because different models tend to perform well for different aspects of climate, and because structural differences between models produce divergent projections, no single model can be considered universally most appropriate. Analyses should therefore be conducted across an ensemble of several models, with results considered across the range of projections to account for this structural uncertainty (Schoeman *et al* 2023).

Beyond mean climate: extremes, land use and integrated scenarios

Projected data on climate extremes are, for example, available through ISIMIP or can be derived directly from GCM / ESM output. Future land use is an equally important driver of species responses (Hari *et al* 2026), and projected land-use change varies substantially depending on the socioeconomic scenario assumed. The Land Use Harmonization project (LUH2) provides annual gridded land-use scenarios consistent with CMIP6 SSP pathways, covering the period until 2100 at 0.25° spatial resolution (Hurtt *et al* 2020). ISIMIP additionally provides harmonized land-use and land-management projections for three scenarios until 2100 at 0.5° resolution from two land-use models (IMAGE and MAgPIE), which account for climate impacts on yields, water availability and carbon stocks and are consistent with the ISIMIP3b climate input data (Molina Bacca *et al* 2025).

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All authors declare no conflict of interest.

Data Accessibility Statement

All data generated and analyzed for this study are included in the Supplementary files.

Figures and tables

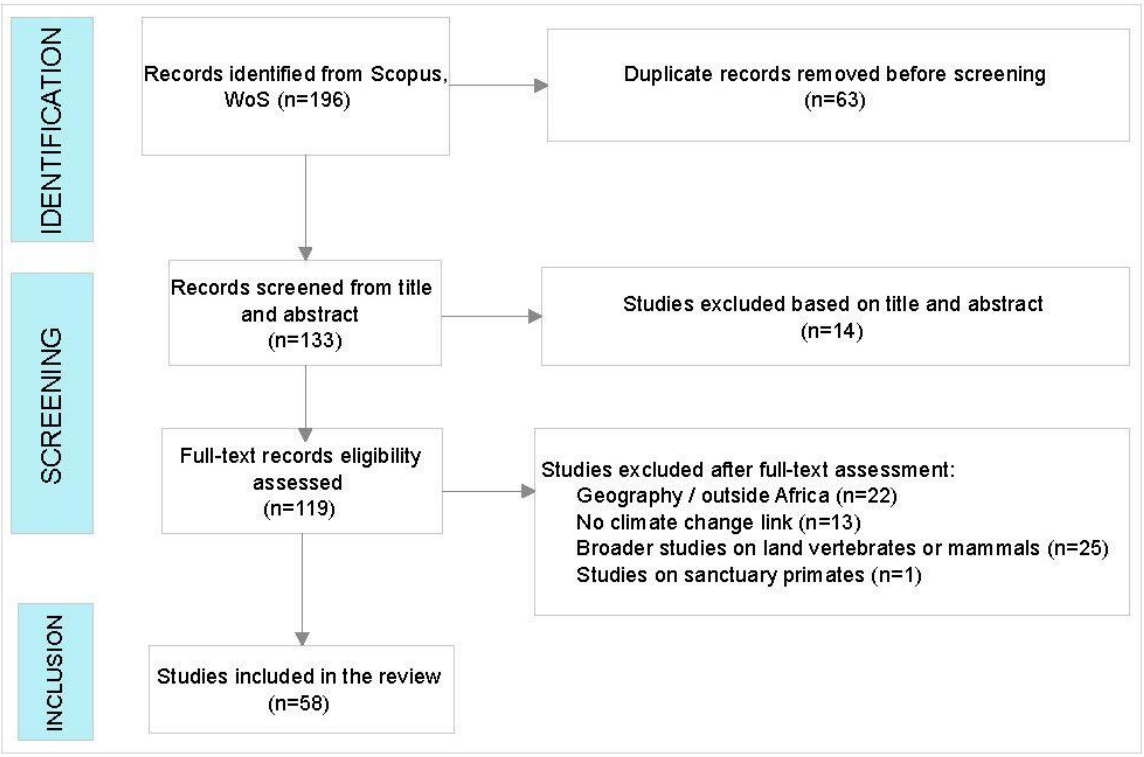


Figure 1. Visual diagram of PRISMA-aligned identification of relevant studies.

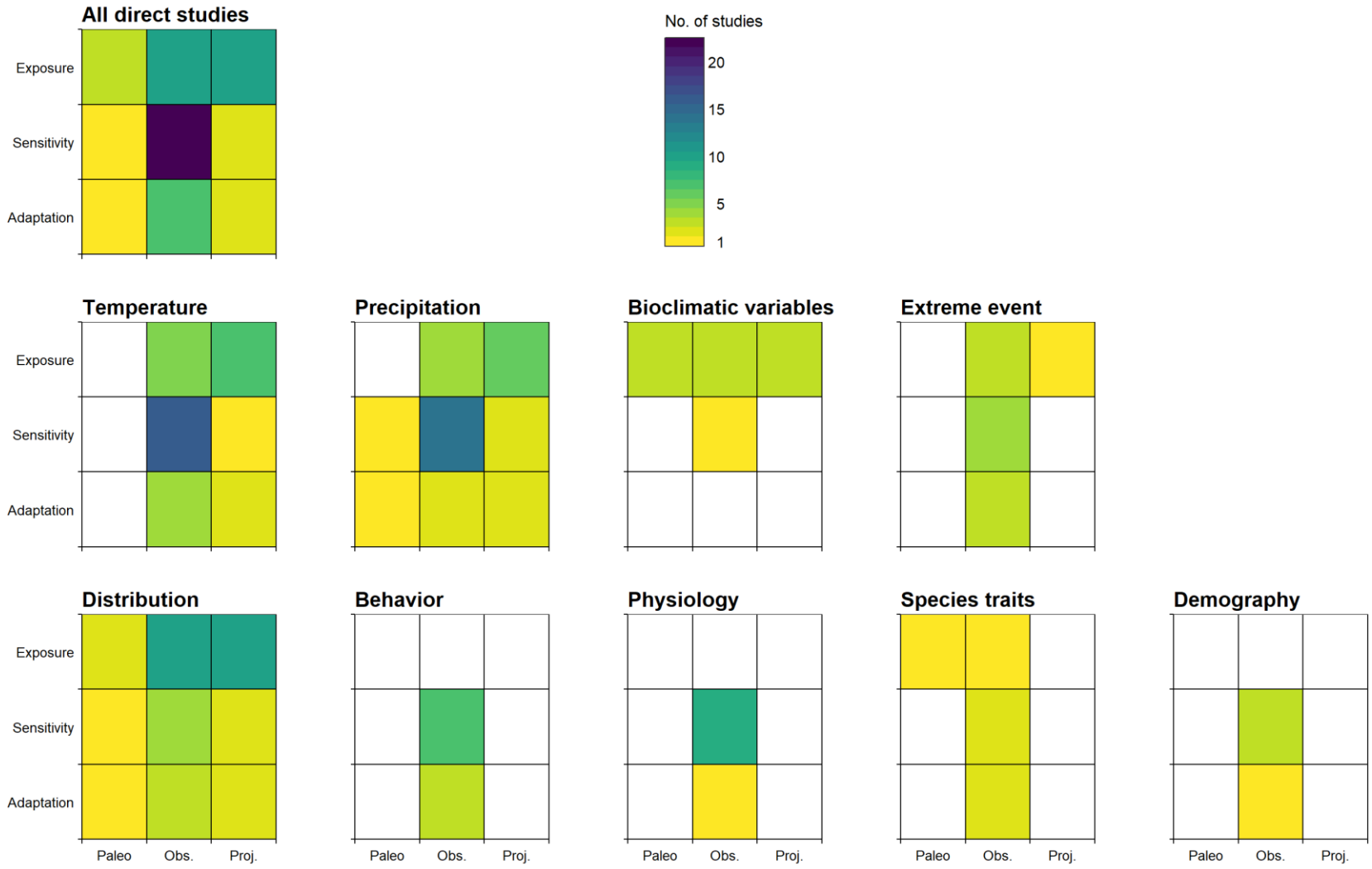


Figure 2. Number of studies along temporal dimension (paleoclimate, observed, projected) and vulnerability dimension (exposure, sensitivity, adaptive capacity) for all studies investigating climate change impacts on primates directly (i.e., 'direct' studies, n=44), second row: climatic variables investigated, third row: type of response variable investigated.

Table 1. Words used for the literature search

Keywords	Search term
Climate change	temperature shift, global warming, climate variability, rainfall, extreme events, heat, cyclone, fire, sensitivity, exposure, adaptive capacity
Primate taxa	primates, monkeys, apes, lemurs, prosimians
Africa	Sub-Saharan Africa, tropical Africa, Madagascar, SSA

Table 2. Evidence of climate change impacts on African primates in the literature reviewed for this study (58 studies, Supplementary table 1). Empty cells imply that this particular combination of vulnerability dimension, impact type and response variable was not investigated.

Climatic variable	Response variable	Observed exposure	Observed sensitivity	Observed adaptive capacity
Temperature changes & heatwave	Occurrence and distribution	African ape sites exposed to increase in temperature (Kiribou *et al* 2024), Eulemur species are exposed to temperature stress (Kamilar and Tecot 2016), large-scale exposure across primate ranges (Yang et al. 2025).	Changes in baboon species range associated with temperature variation (Wango *et al* 2019), chimpanzee occurrence linked to temperature gradients (Wessling *et al* 2020)	Mean temperature and temperature variation belong to strongest predictors of lemur extinction risk (Brandon *et al* 2024)
	Demography (e.g., fertility, survival)		Reduced fertility in blue monkeys with higher temperatures (Campos *et al* 2017), lower survival of grey mouse lemur with increasing temperature (Ozgul *et al* 2023)	
	Behavior		Samango monkeys spend more time feeding with colder temperatures (Coleman *et al* 2021)	Mountain gorillas drink more when maximum daily temperatures are high (Wright *et al* 2022), sifakas hug trees for thermoregulation when temperatures are above 30°C (Chen-Kraus *et al* 2023)
	Physiology (e.g., hormonal changes, metabolic rate)		Higher metabolic rate in sportive lemur in the (lean) cool and dry season (Bethge *et al* 2017), cold-stress leads to increased glucocorticoid levels in geladas (Tinsley	

			Johnson *et al* 2018) and in samango monkeys (LaBarge *et al* 2022), heat stress leads to higher cortisol levels in chimpanzees (Wessling *et al* 2018b)	
Precipitation changes & drought	Occurrence and distribution	Species exposed to drought conditions globally (Yang *et al* 2025), and, for example, specifically vervet monkeys (Young *et al* 2019), ring-tailed lemurs (Fardi *et al* 2018), and Verreaux's sifaka (Veilleux *et al* 2024)	Changes in bamboo lemur occurrence linked to length of dry season (Eronen *et al* 2017)	Annual precipitation and precipitation seasonality not predictors of lemur extinction risk (Brandon *et al* 2024)
	Demography		Increase in mortality in vervet monkeys during droughts (Young *et al* 2019), reduced fertility and infant survival in sifakas due to reduced rainfall, and reduced fertility in blue monkeys (Campos *et al* 2017), lower survival of grey mouse lemur with reduced rainfall (Ozgul *et al* 2023)	
	Behavior		Sportive lemurs spent less time travelling and more time resting with less rainfall (Mandl *et al* 2018), vervet monkeys spent more time resting during droughts (Young *et al* 2019), bamboo lemurs spend more timed feeding on bamboo culm with lower rainfall (Eronen *et al* 2017)	22% of all primate taxa assessed to be vulnerable (sensitivity + adaptive capacity) to drought (Zhang *et al* 2019)
	Physiology		Drought: increase in faecal glucocorticoid in vervet monkey (Young *et al* 2019), increase in hair cortisol concentrations in ring-tailed lemurs (Fardi *et al* 2018), higher metabolic rate in sportive lemurs in the (lean) cool and dry season (Bethge *et al* 2017); Reduced rainfall: increased glucocorticoid levels in samango monkeys (LaBarge *et al* 2022), chimpanzees have elevated creatinine levels both, in savanna and forest environments, suggesting (seasonal) dehydration stress (Wessling *et al* 2018b, 2018a)	

Flooding	Occurrence and distribution	Primates globally exposed to flooding (Yang *et al* 2025), chacma baboons and vervet monkeys exposed to flooding after cyclone (Beardmore-Herd *et al* 2025)	Changes in spatial distribution and relative abundance for chacma baboons and vervet monkeys (Beardmore-Herd *et al* 2025)	
	Demography			
	Behavior			
	Physiology			
Landslides	Occurrence and distribution	landslides most prevalent natural disaster primates globally exposed to (Yang *et al* 2025)		
	Demography			
	Behavior			
	Physiology			
Tropical cyclones	Occurrence and distribution	Primates globally exposed to cyclones (Ameca *et al* 2023, Yang *et al* 2025)		
	Demography			
	Behavior		16% of all primate taxa assessed to be vulnerable (sensitivity + adaptive capacity) to tropical cyclones (Zhang *et al* 2019)	60% of primates globally exposed assessed to have low adaptive capacity, 15% high capacity (Ameca *et al* 2023); 16% of all primate taxa assessed to be vulnerable (sensitivity + adaptive capacity) to tropical cyclones (Zhang *et al* 2019)
	Physiology		Higher levels of hair cortisol concentrations in sub-adult ring-tailed lemurs, and body	

			weight was lowest in post-cyclone periods for all age classes (Fardi *et al* 2018)
Wildfire	Occurrence and distribution	Primates globally exposed to wildfire (Yang *et al* 2025)	
	Demography		
	Behavior		
	Physiology		

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