Climate change impacts on non-human primates: What have we modelled and what do we do now?

by

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Chapter 6

In

PRIMATES IN ANTHROPOGENIC LANDSCAPES: EXPLORING PRIMATE BEHAVIOURAL FLEXIBILITY ACROSS HUMAN CONTEXTS

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ABSTRACT

Climate change will be a key influence on primates in the twenty-first century, potentially exacerbating the effects of habitat loss and anthropogenic activities to drive vulnerable species closer to extinction. There are many ways to assess species' vulnerability to climate change, including modelling approaches of three main types: trait-based models, species distribution models and mechanistic models. In this chapter, we survey the literature on climate change models as applied to primates, including the type(s) of model made and the predictions obtained. Most primate genera (62 of 80) have been subject to ecological modelling, though there are no future projections for lemurs and no palaeoclimate models for lorises, tarsiers or platyrrhines. Maximum entropy methods predominate even though direct comparisons have shown that these tend to predict more severe habitat losses when used uncritically. Most of the taxa modelled to date have been predicted substantial habitat losses by 2100, with significant variation within each taxonomic group.

KEYWORDS: climate change, modelling, anthropogenic impacts, ecological niches, conservation, habitat loss, distributions, species distribution model

1. INTRODUCTION

Climate change is expected to become a major factor driving human and non-human primate survival in the Anthropocene. While climate change impacts may never exceed those of land-use changes and trade, they will very likely exacerbate the effects of these other threats (Gouveia et al., 2016; Struebig et al., 2015 Titeux, 2017; Korstjens and Hillyer 2016). Therefore, a discussion about the effect of anthropogenic factors on non-human primate (henceforth ‘primate’) survival is not complete without some consideration of climate change. Primate vulnerability to climate change is determined by the level and type of changes the species will experience in its geographical range (exposure) coupled with the biological traits that determine how well the species can cope with (sensitivity) or adapt to (adaptability) the predicted changes (Foden et al. 2019; Foden and Young 2016; Korstjens and Hillyer 2016).

Many regions where primates occur are expected to undergo pronounced climatic changes (Graham et al. 2016, Carvalho et al. 2019, Zhang et al. 2019a), with increased maximum temperatures, reduced or excessive rainfall, increased seasonality, and an increased frequency and intensity of extreme events (cyclones and droughts) likely to be the biggest threats to primates. Across primate-occupied regions, mean temperature increases are predicted to be 10% greater than the global average (i.e. for every 1°C increase globally, primate ranges will heat up by 1.1°C; Graham et al. 2016). More worryingly, maximum temperatures are likely to increase by >2°C across primate ranges, with some areas suffering up to 5-7°C increases, taking these temperatures well above the physiological limit for primates (Carvalho et al. 2019). Greatly increased rainfall is predicted for 8% of primate species whilst 4% will see large reductions (>3% increase or decrease per 1°C mean global warming respectively; Graham et al. 2016). Seasonality, an important predictor of species’ geographical ranges (Williams et al. 2021in press), is predicted to become more extreme across primate ranges. Temperature averages, rainfall patterns and seasonality are major determinants of the vegetation cover and productivity of primate habitats. Climate change can exacerbate droughts and cyclones which affect 26% and 18% of primate species respectively (Zhang et al. 2019a) and can lead to devastating instant mortality (Campos et al. 2020). Finally, climate change may have indirect effects on primates by (for instance) changing the patterns of other anthropogenic impacts on them and their habitats. We are still far from producing an exhaustive list of the ways climate change can alter primate lives.

1.1 ASSESSING SPECIES VULNERABILITY TO CLIMATE CHANGE: MODELLING APPROACHES

Models aimed at assessing species' vulnerability to climate change can be divided into three categories of increasing complexity, each with a different suitability for assessing sensitivity, exposure and adaptive ability (Foden et al. 2019; Korstjens and Hillyer 2016; Figure 1). First, trait-based approaches use expert opinion and published knowledge to determine how a species is likely to respond to or cope with particular climate changes based on their biological traits and inferred relationships between traits and vulnerability (e.g. Zhang et al. 2019a). Second, correlative approaches (i.e. species distribution models often called niche or climate envelope models) investigate how current species distributions are influenced by climatic conditions and use these relationships to predict how species will be distributed under future climatic conditions. Finally, mechanistic approaches look at the underlying traits and physiological processes (mechanisms) that determine environment-species relationships to predict how species will be able to cope with and respond to changes based on physiology, behaviour or time budgets (e.g. Dunbar et al. 2009).

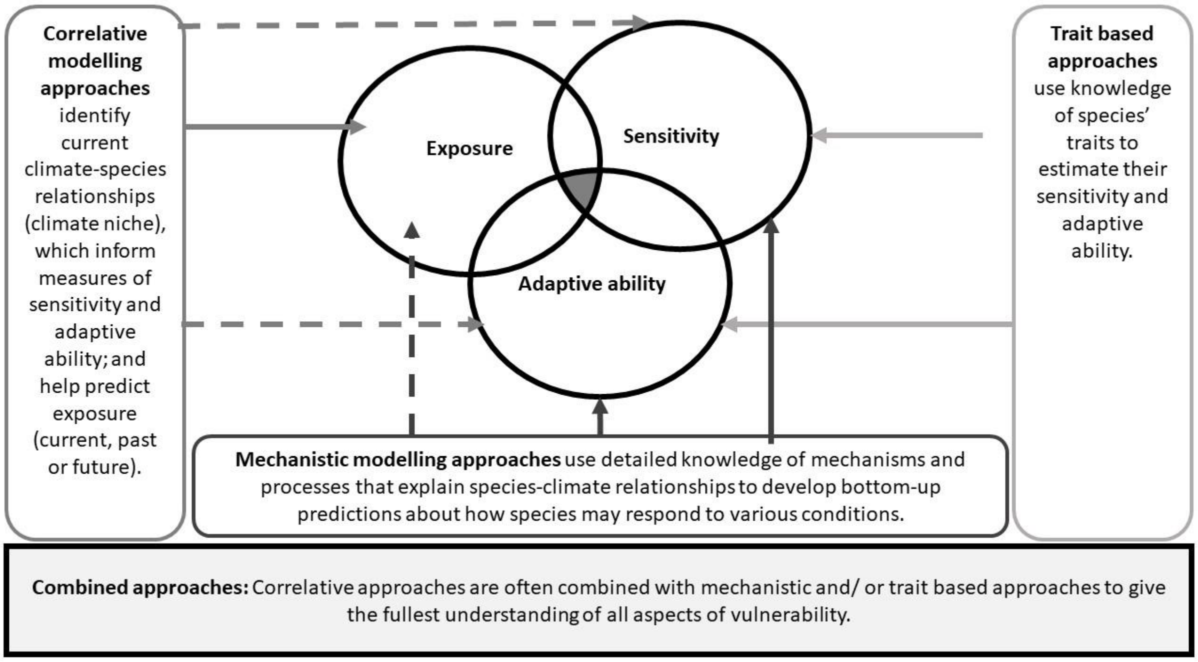

Figure 1: Simplified schematic representation of the relationships between the three main components of a species' vulnerability and the types of vulnerability assessment approaches used to estimate species' vulnerability to climate change. Knowledge of each of these elements (sensitivity, exposure, and adaptive ability) provide the best estimate of actual vulnerability of species (dark grey overlap area in Venn diagram). Solid arrows show the most basic outcome of different approaches and dashed lines show further more indirect outcomes or outcomes achieved by combining the approaches. Foden and Young (2016) provide an extensive overview of vulnerability indices and modelling approaches.

Species distribution models (SDMs) identify which areas are most suitable for a particular taxon, as identified by environmental conditions that describe the species' environmental niche (Elith and Leathwick 2009; Norberg 2019). They best explain exposure but also provide important climate niche information to help understand sensitivity and adaptive ability, often used in trait-based and mechanistic approaches (Figure 1). Once a taxon's environmental niche is established based on current distributions, the models can be used to identify other suitable locations elsewhere or in the past or future. SDMs require input data on the environmental conditions at locations where a species is present to compare against conditions where the species is absent. Due to lack of knowledge of absence, many models are actually developed using presence data and 'psuedo-absences' or background locations, i.e. locations that are randomly selected from a predetermined area (e.g. outside the known distribution area) (Santini et al. 2021; Guillera-Arroita et al. 2015). How these pseudo-absences are selected can greatly affect the reliability of the SDM but is not always given sufficient consideration (for a critical review and test see Santini et al. 2021). The variables that are included in establishing this environmental niche depend on the information and computational resources that are available to the researchers, as well as the research question. Recent exponential growth in accessible global datasets on environmental conditions (e.g. landscape cover, climatic conditions, human footprint) and modelling approaches can make it difficult to keep up with best practice (Araújo et al. 2019; Zurell et al. 2020; e.g. Norberg et al. 2019 review 33 statistical SDM approaches).

In this chapter, we systematically survey the literature covering modelling of non-human primate responses to climate change. In particular, we consider the potential presence and manifestation of taxonomic bias, explore the state of knowledge for each major primate group, and summarise predictions of habitat changes under future climate conditions.

2. SYSTEMATIC METHOD

We searched the literature for modelling studies of the 80 extant non-human primate genera in the IUCN Red List of Threatened Species v. 2020.3 (IUCN 2020) using the broadest academic database, Google Scholar (Gusenbauer 2019). Search terms included the genus name, "species distribution model" and "ecological niche model", linked with Boolean operators. Where we could find no relevant literature for a genus, we refined the taxonomic search term (e.g. using alternative genus names or adding the rest of the binomial) and finally widened our search using the search term “climate change model”.

For each genus we sorted the resulting papers by relevance and selected up to four for detailed analysis (the modal number of relevant hits per genus was 2). Where a genus had more than four relevant papers (which affected the great apes, *Hylobates, Macaca*, *Rhinopithecus*, *Cercopithecus*, *Ateles*, *Aotus*, *Alouatta*, *Saguinus* and *Sapajus*), we read abstracts and methods of all we found and selected a representative sample of four that included (1) as many species as possible; (2) a range of approaches, if several had been used; and (3) predictive and/or palaeoclimate studies if they had been done. This meant, for instance, that for the best-studied genera we excluded some very small-scale studies (especially where they modelled a single population or a region rather than a species' full range). We also sometimes found Masters theses and then papers deriving from the same models (we retained the peer-reviewed papers) or research teams which had produced a series of papers each considering a different species but using the same method and scenario (here we chose a representative example or, if it existed, a recent synthesis covering multiple species). For our final literature sample, we then performed a content analysis by extracting information on climate change scenario(s) and date(s) modelled, modelling approaches, focus and scale (taxon-specific, regional or larger), and the main aims and findings.

3. RESULTS

Over half the studies we found dated to 2018-2021. All the major primate groups have been modelled, though coverage ranged from 30-100% of genera (see Figure 2).

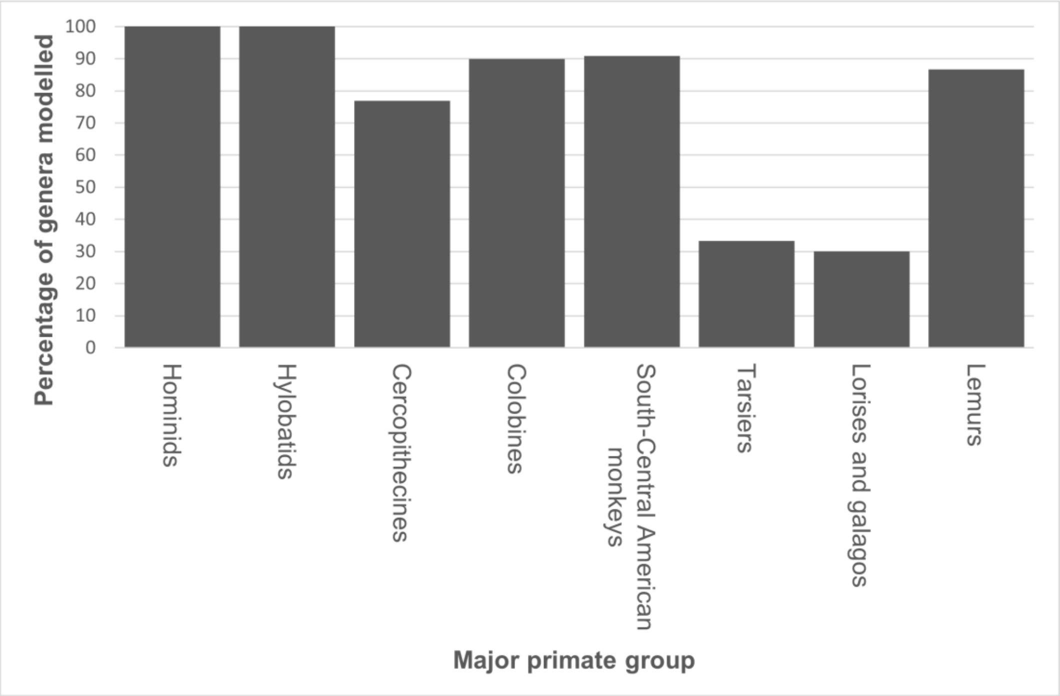

Figure 2: the percentage of genera that have been modelled, arranged by major taxonomic group.

The taxonomic differences in coverage that we observed differed slightly from the bias in favour of apes and lemurs found in the wider climate change literature (Bernard and Marshall 2020) and are less pronounced than those seen in primatological field studies (Bezanson and McNamara 2019).

Correlative species distribution models dominated our literature (Figure 3). A few studies used mechanistic time-budget models (Dunbar, 1998 on *Theropithecus*) or trait-based biophysical models (Stalenberg 2019). The majority of the correlative SDMs used maximum entropy modelling, either as a stand-alone tool (using Maxent software; Phillips et al., 2006) or in R (54/89 studies, 65.1%). Ensemble modelling, using multiple approaches (including maximum entropy, general and generalised linear models) was used in 15 studies (18.1%). Only 3 (3.6%) used generalised linear models, with all other methods accounting for 1-2.5% (one or two papers) each. There were some differences among taxonomic groups, with maximum entropy modelling dominating even more where a group was understudied or subject to one or two broad works rather than numerous specific ones.

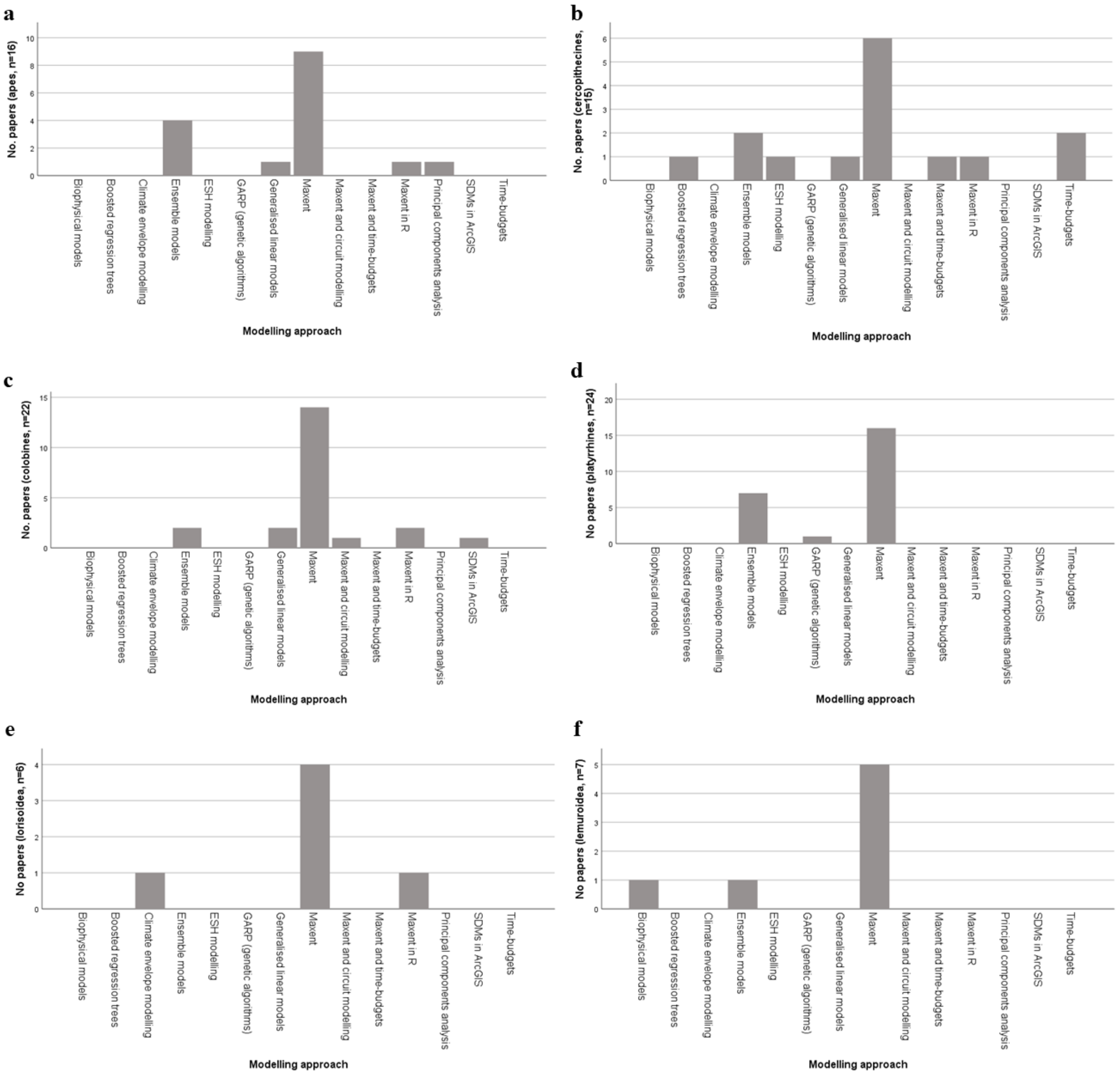

Figure 3: modelling approaches used for works on each major primate taxonomic group: a) apes; b) cercopithecines; c) colobines; d) platyrrhines; e) lorises and galagos; f) lemurs. The tarsiers are excluded, because we found only one relevant paper, which used maximum entropy modelling in R. Full details of each paper can be found in supplemental tables 1-7.

Most, 54.8% of studies, only modelled the present day, while 33.3% projected into the future and 10.7% into the past. This pattern varied by group (see Figure 4; there were no future projections in lemurs; only future but no palaeoclimate models in lorises and galagos and platyrrhines). Present-only models were generally conservation orientated, looking at fragmentation, primate distributions and conservation planning. Common themes throughout the literature include climate change, ecology, anthropogenic impacts, and conservation (Figure 5).

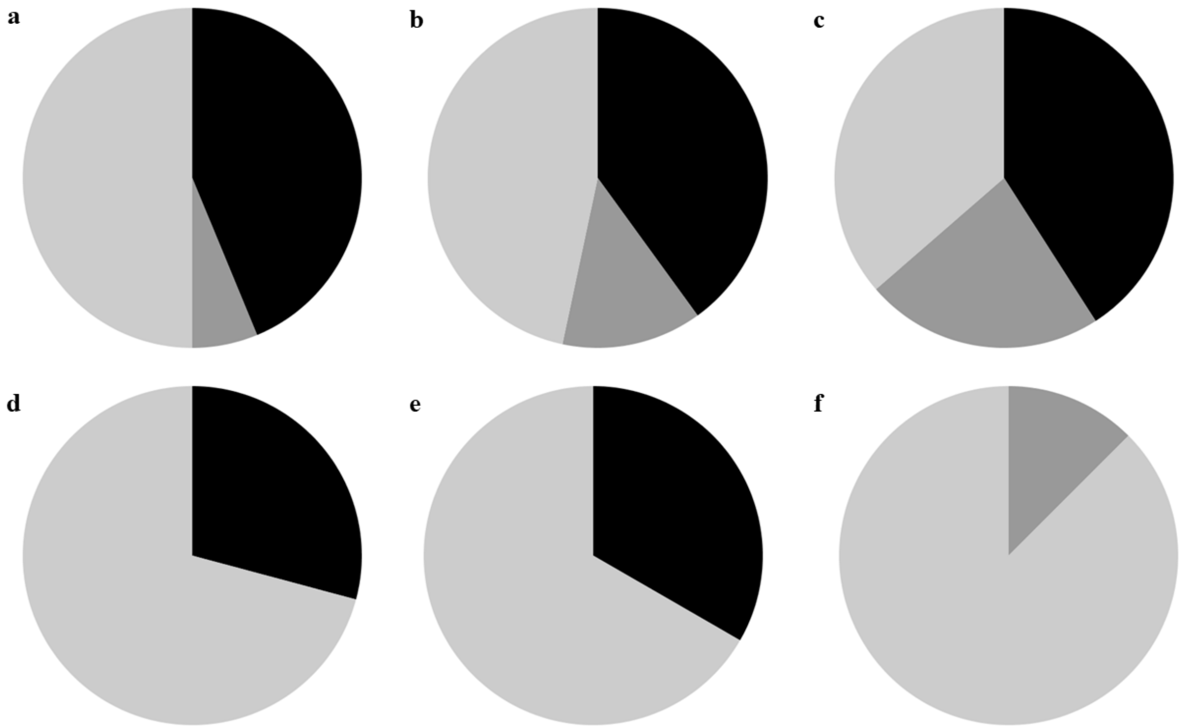

Figure 4: periods covered by modelling studies of the major primate groups: a) apes; b) cercopithecines; c) colobines; d) platyrrhines; e) lorises and galagos; f) lemurs. Black denotes papers projecting the future, mid-grey include papers examining palaeoclimates, pale grey include papers examining present alone. Tarsiers are excluded because only one paper (which projected to 2050) was found.

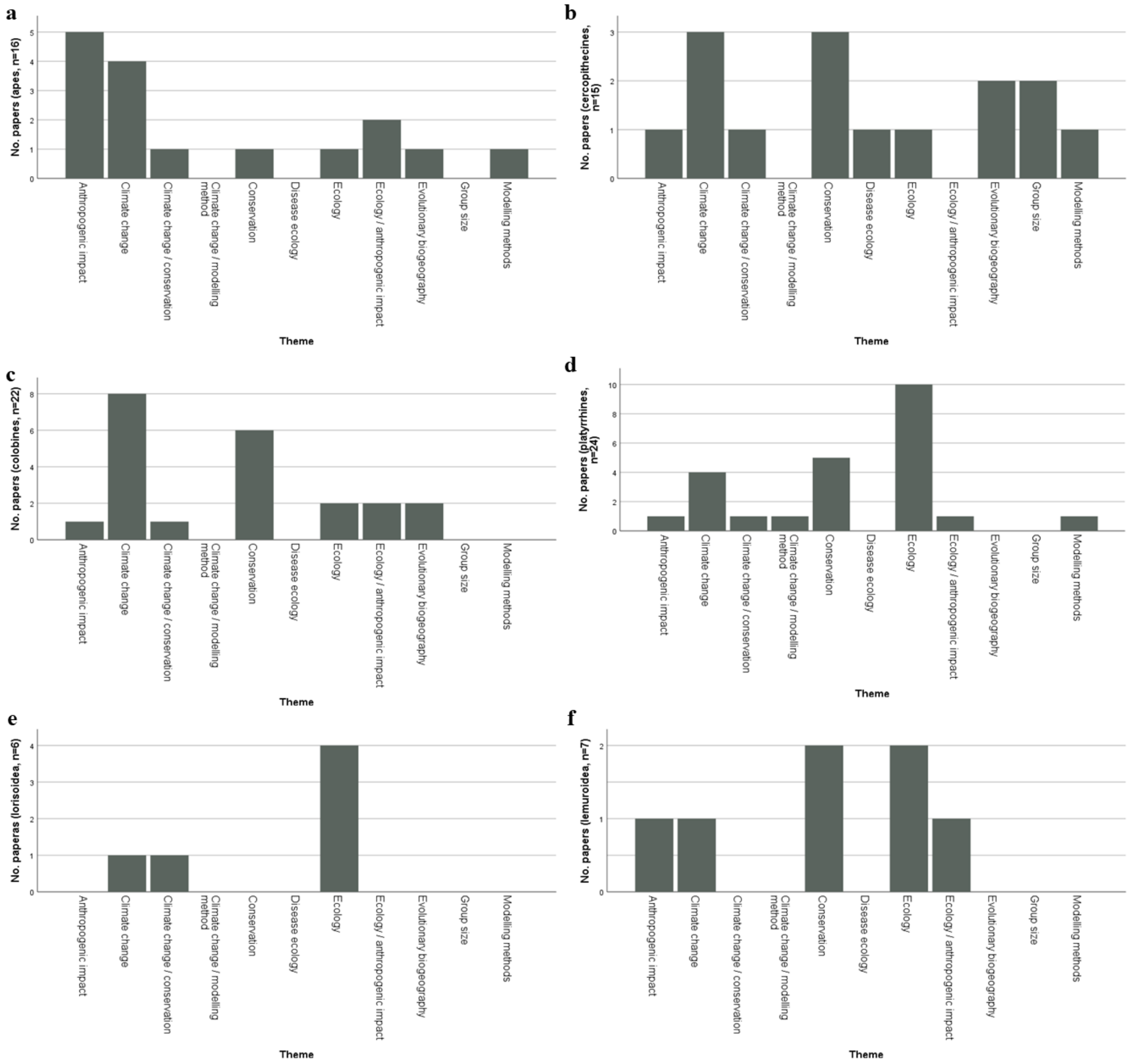

Figure 5: common themes in modelling literature for each major primate group: a) apes; b) cercopithecines; c) colobines; d) platyrrhines; e) lorises and galagos; f) lemurs. Tarsiers are excluded, as only one paper was found – it explored climate change impacts on biodiversity.

3.1. APES

All seven ape genera have been the subject of modelling studies, but only *Hylobates* and the hominids had >4 studies each. Maximum entropy models were used in 62.5% and ensemble approaches in 25% of studies. Only Barratt et al. (2020) explored palaeoclimate models, eight studies modelled the present (Wich et al. 2012; Etiendem et al. 2013; Ario et al. 2018; Singh et al. 2018; Rahman et al. 2019; Tran and Vu 2020; Bonnin et al. 2020; Yuh et al. 2020) and seven predicted the future (named below).

Outcomes of future predictions varied by taxon and approach. Mwambo (2010) and Carvalho et al. (2021) predicted substantial habitat losses for *Pan* and *Gorilla* by 2090. Thorn et al. (2013), however, found that these losses were typical only when using 'standard' correlative models, and a limiting factor model predicted minimal change for mountain gorillas. Predictions of climate change impacts, they concluded, are sensitive to the assumptions of the selected method.

For Asian apes, predictions were more negative. Wich et al. (2016) used land-cover change scenarios to predict substantial population declines for *Pongo abelii* by 2030. Other taxa potentially at high risk included various species of *Hylobates* (Trisurat 2018; Condro et al., 2021), *Pongo abelii* and *Symphalangus syndactylus* (Condro et al., 2021). Potentially better off were *Pongo pygmaeus* (Condro et al., 2021) and *Hoolock hoolock* (Deb et al., 2019), both predicted range increases, while *Hylobates muelleri* and *H. abbotti* were predicted only small changes (Condro et al., 2021). The differences in apparent risk may result from different vulnerability profiles or modelling approaches.

3.2 AFRICAN AND ASIAN MONKEYS

We found models on 10/13 cercopithecine genera (all save *Erythrocebus, Miopithecus* and *Allenopithecus*, though *Chlorocebus* is included only under the older name *Cercopithecus* in Willems & Hill 2009) and 9/10 colobine genera (all but *Procolobus*). Among the 15 studies found, two predicted past distributions (Khanal et al. 2018a; Chala et al. 2019), six predicted the future (listed below) and seven focused on the present (Willems & Hill 2009; Green 2012; Cronin et al. 2015 and 2017, who reported the same models; Moyes et al. 2016; Korstjens et al. 2018; Fuchs et al. 2018; Greenspan et al. 2020).

Predicted outcomes of climate change varied. Dunbar (1998)'s time-budget model predicted that *Theropithecus gelada* populations will fragment as climates warm), while Hill and Winder (2019) predicted that 3/6 *Papio* species might suffer substantial habitat losses. Condro et al. (2021) predicted habitat losses by 2050 for eight macaque species, but suggested *Macaca ochreata* and *M. siberu* would be less affected. *Mandrillus leucophaeus* may experience substantial habitat loss from earlier on in the 21st century than *Cercocebus atys* (Baker and Willis, 2015). Finally, Korstjens (2019) suggested that habitat suitability for *Cercopithecus* would reduce only slightly by 2070. The final study that looked to the future, Ayebare et al. (2013), did not present any species-specific results.

In the colobine literature, there are proportionally more single-species or regional studies than for cercopithecines, particularly in Asia. Of 22 studies, five focused on the past (Moody 2007; Winyoningrum 2013; Ehlers-Smith 2014; Ren et al. 2017; Khanal et al. 2018c), nine predicted the future (see below) and eight focused on the present (McDonald et al. 2019; Cronin et al. 2015 and 2017; Cavada et al. 2017; Singh et al. 2018; Tran et al. 2018; Anh et al. 2019; Atmoko et al. 2020; Khanal et al. 2018b).

Korstjens (2019) suggested that *Colobus* may be more at risk than *Cercopithecus*. At species level, Baker and Willis (2015) predicted substantial habitat loss for *C. polykomos* (whilst *C. vellerosus*, may be unaffected along with *Piliocolobus pennantii*). *P. badius*, however, is predicted range loss by all their models and *P. preussi* may lose habitat by 2040.

In Asia, *Pygathrix* (Vu et al., 2020; Tran et al., 2020), *Rhinopithecus* (Luo et al., 2015; Zhang et al., 2019b) and *Semnopithecus* species (Bagaria et al., 2020) are predicted substantial habitat loss. Condro et al. (2021) predicted complete habitat losses for two species of *Trachypithecus*, *Simias concolor* and six species of *Presbytis.* They found that two more *Presbytis* species would experience smaller habitat losses, while three would be stable or increase their habitats. Finally, Zhao et al. (2019) suggested that *Rhinopithecus bieti* might lose 8-22% of its suitable habitat by 2050 unless anthropogenic land-use changes were controlled, in which case, their suitable habitat might increase.

3.3 SOUTH AND CENTRAL AMERICAN MONKEYS

We found models for 20 of 22 platyrrhine genera (Platyrrhini), all save *Leontocebus* and *Brachyteles*. Of these, none modelled the past, seven the future (see below) and seventeen the present (Holzmann et al. 2015; Vidal-Garcia and Serio-Silva 2011; Calizto-Peréz et al. 2018; Clément et al. 2014; Hasui et al. 2017; Helenbrook & Valdez 2020; Shanee et al. 2015; Ortega Huerta 2007; Boubli & De Lima 2009; Guy et al. 2016; Moraes et al. 2019; Campos and Jack 2013; Rezende et al. 2020; Ochoa-Wuintero et al. 2017; Garbino et al. 2015; Howard et al. 2015; De Marco et al. 2020).

For platyrrhines as for colobines and cercopithecines, projections of climate change impacts often also include the impact of deforestation and other anthropogenic changes, and studies that expressly separate these often suggest forest loss will be more damaging. *Lagothrix lagothricha* is predicted a 13% loss of suitable habitat due to climate change, but 18% where forest loss continues apace (Linero et al., 2020). Other species predicted severe habitat losses included *Callithrix flaviceps*, *C. pencillata* and *C. aurita* (though other members of the same genus were less affected; Braz et al., 2019), *Alouatta belzebul*, *Sapajus flavius* and *S. libidinosus* (Moraes et al., 2020), *Aotus miconax, Lagothrix flavicauda* and, if land-use change continues alongside climate change, *Plecturocebus oenanthe* (Shanee, 2016).

Several platyrrhine studies focused on broad biodiversity measures and how biodiversity might shift or decline as climates change. Sales et al. (2017) found that biodiversity of taxa including primates was likely to decline in the Amazon, and Sales et al. (2020) suggested that overall, the contribution of primates to seed-dispersal in this area, based on modelled range area and dispersal potential, is likely to decline substantially. Sales et al. (2019) found that 20% of 80 primate species might expand their ranges as a result of climate change, if they can disperse as well as they can today. If fragmentation prevents dispersal of platyrrhines through the Amazon, these 80 species will lose on average 90% of their suitable habitat.

3.4 TARSIERS

Only one of three tarsier genera (genus *Tarsius*) has been modelled, and only once. Condro et al. (2021) used maximum entropy modelling in R to explore climate change impacts on Indonesian biodiversity, and included 8 species. They predicted total habitat loss by 2050 for six species, near complete loss for *Tarsius dentatus* and roughly stable habitat for *T. pumilus*.

3.5 LORISES AND GALAGOS

The lorises and galagos (superfamily Lorisoidea) were also rarely studied, with only one of six genera of Galagidae and two of four among Lorisidae the subject of any models. We found no palaeoclimate models, two that predicted the future (see below) and four that focused on the present (Thorn et al. 2009; Nekaris and Stengel 2013; Voskamp et al. 2014; Kumara et al. 2021).

Condro et al. (2021) predicted total habitat loss for *N. javanicus*, and ~75% loss for *N. bacanus*. The remaining five taxa (*N. kayan*, *N. hilleri*, *N. borneanus*, *N. coucang* and *N. menagensis*) were all predicted small increases of up to ~25% of the current extent (Condro et al., 2021). Erasmus et al. (2002) suggested significant shifts in overall biodiversity of South African animal communities, including *Galago moholi*, by 2050.

3.6 LEMURS

We found seven works specifically focusing on modelling the niches and climatic vulnerabilities of Lemuroidea, two of which (Peacock, 2011 and Herrera et al., 2018) cover a wide range of taxa. In fact, beyond these two papers, only *Lepilemur* (Stalenberg, 2019) and *Eulemur*, which was by far the best studied, were modelled. *Allocebus* was not studied at all. Among these, none addressed the future, one (Stalenberg 2019) reconstructed the past and six (Peacock 2011; Herrera et al. 2018; Blair et al. 2013; Kamilar and Tecot 2016; Mercado Malabet et al. 2020; Ormsby 2019) explored the present.

The only model of the effects of climate change in lemurs was Stalenberg (2019)'s biophysical model. Biophysical models estimate a species' thermal niche and water requirements and compare physiological needs to environmental conditions to identify suitable habitats for it. Stalenberg's model found that *Lepilemur leucopus* was at higher risk of thermal stress in the 1975-2005 than the 1931-1960 time period.

4. DISCUSSION AND CONCLUSIONS

Climate change impact on primates is still a relatively new area of research, with over half of the studies published 2018 onwards, yet it is no doubt an important one. Our systematic review shows that there are still relatively few studies out there, and fewer than half of the species distribution models that have been built have been used to predict the future. Efforts are not equally distributed across genera, with apes and large-bodied monkeys being the best represented, a bias that we see in the wider primatological literature (Bezanson and McNamara, 2019; Hawes et al., 2013). Bezanson and McNamara (2019) suggest that taxonomic bias may be related to the presence of long-term field sites and publication bias. Although modelling work is often desk-based, it does rely on a reasonable knowledge of the localities where the target species is found.

In the wider context of publishing in primatology, the small study counts we found for this specific topic highlight it as an understudied subject. To date, we have very limited understanding of how climate change is potentially going to affect primates, and with 2050 (one of the predicted scenarios used in climate modelling) less than 30 years away, we urgently need to make meaningful predictions and adapt subsequent conservation strategies. Those studies we do have suggest that primates will need to shift ranges to accommodate changing climatic conditions (Estrada et al., 2017; Schloss et al., 2012), with consequences for their management and conservation. Primate responses to changing climates will be species-specific (Condro et al., 2021; Schloss et al., 2012 and this study), so we cannot rely on generalisations across subfamilies. The sooner we identify the potential impacts of climate change on primates, the longer we give ourselves to implement the necessary steps to mitigate effects and avoid population declines.

Modelling efforts did not seem to correspond with extinction risk, i.e. species classified by the IUCN as “critically endangered” or “endangered” were no more likely to be the focus of these studies. In fact, some endangered species (*Prolemur simus*, *Macaca pagensis*) have yet to be studied this way. Species that are already struggling may face even more challenging futures that we cannot accurately prepare for and mitigate if we do not have predictions of what the future may mean. This is yet again a pattern in the wider literature (Bezanson and McNamara, 2019) and may be a result of data scarcity. Although modelling can draw on online or published pools of data, such as the Global Biodiversity Information Facility (GBIF) or iNaturalist, sometimes datasets for a species are still missing, small, inaccurate or of poor quality (Maldonado et al., 2015), making it difficult to build accurate, high-quality models.

Both this review and the literature within it emphasise the need for more foundational knowledge on many primate species. When we are unsure on current ranges, habitat preferences, and a species’ ability to cope with anthropogenic factors, accurate and meaningful projections may be impossible and we run the risk of overgeneralisation. Some species may gain incidental protection from sharing their habitats with others we have modelled, but this is not the ideal given that responses are so species-specific (Schloss et al., 2012; Pacifici et al., 2017). It is also important to note that simply modelling distributions based on perceived correlations between occurrence and climate conditions may not give us the full picture. Herrera et al.’s (2018) study found that food tree distribution was a more accurate predictor for lemur distribution than climate. Indeed, different aspects of the environment will influence different species, with arboreal species perhaps more concerned with forest connectivity than terrestrial ones, and these factors can also affect population density (Pozo-Montuy et al., 2011).

Correlative methods, and specifically maximum entropy models, were by far the most common approach we found, but climate change modellers are far from reaching consensus on methodology. With SDMs there is ongoing disagreement on how small a sample size is appropriate and how accurate small-sample studies are (Wisz et al., 2008; Santini et al., 2021). Occurrence data used in studies of rare or cryptic species in particular is likely to have been opportunistically collected (and thus not randomly sampled or reflective of entire populations). Conducting studies on the species that have established field sites simply because they are the taxa we have sufficient high-quality data for is likely to unintentionally reinforce taxonomic biases. Additionally, animals do not exist in closed systems. Many external factors that are not commonly included in SDM studies can influence primate distributions. For example, anthropogenic and biotic factors (such as natural disasters) ultimately will play a role in shaping current and future distributions (Graham et al., 2016; Kamilar and Tecot, 2016) and, while some primatological studies included these factors, this was rare. Studies that fail to include anthropogenic layers risk over-estimating primate ranges (Kamilar and Tecot, 2016). SDMs also do not take into account behavioural flexibility, or the issues of sensitivity and adaptability mentioned in our introduction. As a more positive note, it is worth our recognising that some primate species have adapted fairly successfully to human-dominated landscapes, persisting in urban areas (Aguiar et al., 2014; Jaman and Huffman, 2013). Human encroachment and urbanisation may impact such species less than others. Overall, while the picture emerging from existing models of primate responses to climate change may seem grim, we would like to end by proposing that there are significant gains to be made for primatologists and conservationists if we work to develop better methods and simultaneously generate new knowledge about our models' predictive abilities.

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Supplemental Tables for

Climate change impacts on non-human primates: What have we modelled and what do we do now?

by

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Chapter 6

In

PRIMATES IN ANTHROPOGENIC LANDSCAPES: EXPLORING PRIMATE BEHAVIOURAL FLEXIBILITY ACROSS HUMAN CONTEXTS

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Supplemental Table 1: modelling studies of hominids and hylobatids including taxonomic focus, modelling approaches, time-periods and broad theme.

Paper	Genera	Modelling approach	Periods		Theme
			Past	Future	
Etiendem et al. (2013)	*Gorilla*	Maxent			Anthropogenic impact
Thorn et al. (2013)	*Gorilla*	Ensemble modelling		✓	Modelling methods
Carvalho et al. (2021)	*Gorilla, Pan*	Ensemble modelling		✓	Climate change
Yuh et al. (2020)	*Gorilla, Pan*	Maxent			Anthropogenic impact
Deb et al. (2019)	*Hoolock*	Maxent		✓	Climate change
Trisurat (2018)	*Hylobates*	Maxent		✓	Climate change
Ario et al. (2018)	*Hylobates*	Principal components analysis			Conservation
Singh et al. (2018)	*Hylobates*	Maxent			Ecology / anthropogenic impact
Condro et al. (2021)	*Hylobates, Pongo, Symphalangus*	Maximum entropy in R		✓	Climate change
Tran & Vu (2020)	*Nomascus*	Maxent			Ecology
Bonnin et al. (2020)	*Pan*	Ensemble modelling			Anthropogenic impact
Mwambo (2010)*	*Pan*	Maxent		✓	Climate change
Barratt et al. (2020)*	*Pan*	Ensemble modelling	✓		Evolutionary biogeography
Rahman et al. (2019)	*Pongo*	Maxent			Anthropogenic impact
Wich et al. (2016)	*Pongo*	Generalised linear modelling		✓	Anthropogenic impact (forest loss scenarios)

Paper	**Genera**	**Modelling approach**	**Periods**		**Theme**
			Past	Future	
Wich et al. (2012)	*Pongo*	Maxent			Ecology / anthropogenic impact

*papers labelled with an asterisk are yet to be peer-reviewed (theses, pre-prints or reports for conservation organisations).

Supplemental Table 2: modelling studies of cercopithecines including taxonomic focus, modelling approaches, time-periods and broad theme.

Paper	**Genera**	**Modelling approach**	**Periods**		**Theme**
			Past	Future	
Cronin et al. (2015, 2017)*	*Allochrocebus, Cercopithecus, Mandrillus*	Maxent			Anthropogenic impact
Korstjens et al. (2018)	*Allochrocebus, Cercopithecus*	Time-budgets			Group size
Baker and Willis (2015)*	*Cercocebus, Mandrillus*	Ensemble modelling		✓	Climate change
Korstjens (2019)	*Cercopithecus*	Generalised linear models		✓	Climate change
Willems and Hill (2009)	*Cercopithecus* (includes what we would now call *Chlorocebus*)	Maxent and time-budgets			Modelling methods
Ayebare et al. (2013)	*Cercopithecus, Lophocebus*	Maxent		✓	Conservation
Khanal et al. (2018a)	*Macaca*	Maxent	✓		Evolutionary biogeography
Moyes et al. (2016)	*Macaca*	Boosted regression tree modelling			Disease ecology
Condro et al. (2021)	*Macaca*	Maximum entropy in R		✓	Climate change / conservation
Greenspan et al. (2020)	*Macaca*	Maxent			Conservation
Fuchs et al. (2018)	*Papio*	Maxent			Ecology
Hill and Winder (2019)	*Papio*	Maxent		✓	Climate change
Chala et al. (2019)	*Papio*	Ensemble modelling	✓		Evolutionary biogeography

Paper	**Genera**	**Modelling approach**	**Periods**		**Theme**
			Past	Future	
Green (2012)*	*Rungwecebus*	Extent of suitable habitat (ESH) modelling			Conservation
Dunbar (1998)	*Theropithecus*	Time-budgets		✓	Group size

*papers marked with an asterisk are yet to be peer-reviewed (theses, pre-prints or reports for conservation organisations.

Supplemental Table 3: modelling studies of colobines including taxonomic focus, modelling approaches, time-periods and broad theme.

Paper	Genera	Modelling approach	Periods		Theme
			Past	Future	
McDonald et al. (2019)	*Colobus*	Maxent			Ecology
Korstjens (2019)	*Colobus*	Generalised linear models		✓	Climate change
Cronin et al. (2015, 2017)*	*Colobus*, *Piliocolobus*	Maxent			Anthropogenic impacts
Cavada et al. (2017)	*Colobus*, *Piliocolobus*	Generalised linear models			Ecology
Baker and Willis (2015)*	*Piliocolobus*	Ensemble modelling		✓	Climate change
Condro et al. (2021)	*Presbytis*, *Nasalis*, *Simias*, *Trachypithecus*	Maximum entropy in R		✓	Climate change / conservation
Ehlers-Smith (2014)	*Presbytis*	Species distribution modelling in ArcGIS	✓		Ecology / anthropogenic impact
Singh et al. (2018)	*Presbytis*	Maxent			Ecology / anthropogenic impact
Vu et al. (2020)	*Pygathrix*	Maxent		✓	Climate change
Tran et al. (2020)	*Pygathrix*	Maxent		✓	Climate change
Tran et al. (2018)	*Pygathrix*	Maxent			Conservation
Anh et al. (2019)	*Pygathrix*	Maxent			Conservation
Atmoko et al. (2020)	*Nasalis*	Maxent			Conservation
Zhao et al. (2019)	*Rhinopithecus*	Maxent and genetic/ circuit modelling		✓	Climate change

Paper	Genera	Modelling approach	Periods		Theme
			Past	Future	
Luo et al. (2015)	*Rhinopithecus*	Maxent		✓	Climate change
Zhang et al. (2019b)	*Rhinopithecus*	Maxent		✓	Climate change
Ren et al. (2017)	*Rhinopithecus*	Maximum entropy in R	✓		Conservation
Khanal et al. (2018b)	*Semnopithecus*	Maxent			Conservation
Khanal et al. (2018c)	*Semnopithecus*	Maxent	✓		Evolutionary biogeography
Bagaria et al. (2020)	*Semnopithecus*	Ensemble modelling		✓	Climate change
Moody (2007)*	*Trachypithecus*	Maxent	✓		Evolutionary biogeography
Windyoningrum (2013)*	*Trachypithecus*	Maxent	✓		Conservation

*papers marked with an asterisk are yet to be peer-reviewed (theses, pre-prints or reports for conservation organisations).

Supplemental Table 4: modelling studies of platyrrhines including taxonomic focus, modelling approaches, time-periods and broad theme.

Paper	**Genera**	**Modelling approach**	**Periods**		**Theme**
			Past	Future	
Holzmann et al. (2015)	*Alouatta*	Maxent			Ecology
Sales et al. (2017)	*Alouatta*, *Aotus*, *Ateles*, *Callicebus*, *Cebuella*, *Chiropotes*, *Saguinus*, *Saimiri*	Ensemble modelling		✓	Climate change / modelling methods
Vidal-Garcia and Serio-Silva (2011)	*Alouatta*, *Ateles*	Maxent			Ecology
Calixto-Pérez et al. (2018)	*Alouatta*, *Ateles*	Maxent			Modelling method
Clement et al. (2014)	*Alouatta*, *Ateles*, *Cebus*, *Pithecia*, *Saguinus*, *Saimiri*	Ensemble modelling			Ecology
Sales et al. (2019)	*Alouatta*, *Aotus*, *Ateles*, *Cacajao*, *Callibella*, *Callimico*, *Cebuella*, *Cebus*, *Cheracebus*, *Chiropotes*, *Lagothrix*, *Mico*, *Pithecia*, *Plecturocebus*, *Saguinus*, *Saimiri*, *Sapajus*	Maxent		✓	Climate change

Paper	**Genera**	**Modelling approach**	**Periods**		**Theme**
			Past	Future	
Hasui et al. (2017)	*Alouatta, Callicebus, Callithrix, Sapajus*	Maxent			Ecology
Moraes et al. (2020)	*Alouatta, Sapajus*	Maxent		✓	Conservation
Shanee (2016)	*Aotus, Lagothrix, Plecturocebus,*	Maxent		✓	Climate change
Helenbrook and Valdez (2020)*	*Aotus*	Maxent			Conservation
Shanee et al. (2015)	*Aotus*	Maxent			Ecology
Ortega Huerta (2007)	*Ateles*	GARP (genetic algorithms)			Conservation
Sales et al. (2020)	*Ateles, Cebus, Cheracebus, Lagothrix, Pithecia, Plecturocebus, Saguinus, Saimiri, Sapajus*	Maxent		✓	Climate change
Boubli and De Lima (2009)	*Cacajao, Chiropotes*	Maxent			Ecology
Guy et al. (2016)	*Callithrix, Leontopithecus*	Maxent			Ecology
Moraes et al. (2019)	*Callithrix*	Ensemble modelling			Anthropogenic impact
Braz et al. (2019)	*Callithrix*	Ensemble modelling		✓	Climate change
Campos and Jack (2013)	*Cebus*	Maxent			Conservation

Paper	**Genera**	**Modelling approach**	**Periods**		**Theme**
			Past	Future	
Linero et al. (2020)	*Lagothrix*	Ensemble modelling		✓	Climate change / conservatopn
Rezende et al. (2020)	*Leontopithecus*	Ensemble modelling			Conservation
Ochoa-Quintero et al. (2017)	*Mico*	Maxent			Ecology
Garbino et al. (2015)	*Saguinus*	Maxent			Ecology
Howard et al. (2015)	*Sapajus*	Maxent			Ecology
De Marco et al. (2020)	*Sapajus*	Ensemble modelling			Ecology / anthropogenic impact

*papers marked with an asterisk are yet to be peer-reviewed (theses, pre-prints or reports for conservation organisations).

Supplemental Table 5: modelling studies of tarsiers including taxonomic focus, modelling approaches, time-periods and broad theme.

Paper	**Genera**	**Modelling approach**	**Periods**		**Theme**
			Past	Future	
Condro et al. (2021)	*Nycticebus*	Maximum entropy in R		✓	Climate change / conservation

Supplemental Table 6: modelling studies of lorises and galagos including taxonomic focus, modelling approaches, time-periods and broad theme.

Paper	**Genera**	**Modelling approach**	**Periods**		**Theme**
			Past	Future	
Erasmus et al. (2002)	*Galago*	Climate envelope modelling		✓	Climate change
Nekaris and Stengel (2013)	*Loris*	Maxent			Ecology
Voskamp et al. (2014)	*Nycticebus*	Maxent			Ecology
Kumara et al. (2021)	*Nycticebus*	Maxent			Ecology
Condro et al. (2021)	*Nycticebus*	Maximum entropy in R		✓	Climate change / conservation
Thorn et al. (2009)	*Nycticebus*	Maxent			Ecology

Supplemental Table 7: modelling studies of lemurs including taxonomic focus, modelling approaches, time-periods and broad theme.

Paper	Genera	Modelling approach	Periods		Theme
			Past	Future	
Peacock (2011)	*Avahi*, *Cheirogaleus*, *Daubentonia*, *Eulemur*, *Hapalemur*, *Indri*, *Lemur*, *Lepilemur*, *Microcebus*, *Mirza*, *Phaner*, *Propithecus*, *Varecia*	Maxent			Conservation
Herrera et al. (2018)	*Avahi*, *Cheirogaleus*, *Eulemur*, *Hapalemur*, *Indri*, *Lemur*, *Lepilemur*, *Microcebus*, *Propithecus*, *Varecia*	Maxent, with general and generalised linear models to predict densities			Ecology
Blair et al. (2013)	*Eulemur*	Maxent			Ecology
Kamilar and Tecot (2016)	*Eulemur*	Maxent			Ecology / anthropogenic impacts
Mercado Malabet et al. (2020)	*Eulemur*	Maxent			Anthropogenic impact
Ormsby (2019)	*Eulemur*	Ensemble modelling			Conservation
Stalenberg (2019)*	*Lepilemur*	Biophysical (mechanistic) models	✓		Climate change

*papers marked with an asterisk are yet to be peer-reviewed (theses, pre-prints or reports for conservation organisations).

Additional tables in supplemental material:

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