The effect of climate change on the distribution of Canidae

Prediction of current and future distribution of canids.

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ABSTRACT

Land use by humans and climate change have been seriously affecting the distribution of species resulting in a quarter of all known mammals currently threatened with extinction. Here, we modeled the present and future potential distributions of all 36 extant Canidae species to evaluate their response to future climate scenarios. In addition, we tested if canids were likely to experience evolutionary rescue, which could allow some species to adapt to climate change. Our results suggest that global warming will cause most species to lose or maintain their ranges, while a few will have the potential to benefit from future conditions and considerably expand their geographic distributions. Some canids have the potential to experience evolutionary rescue, but *Atelocynus microtis* and *Chrysocyon brachyurus* are two concerning cases that do not show this capacity to adapt given the current pace of climate change. We also reveal that most Canidae hotspot regions are outside protected areas, which may be useful for the identification of key areas for conservation.

KEYWORDS: adaptation, ecological niche models, environmental change, geographical ranges, Haldanes.

33

34 **1 INTRODUCTION**

35 The pace of climate change induced by humans is much faster than predicted previously
 36 (Pimm et al., 2014). Ceballos et al. (2015) showed that the rate of vertebrate species loss over
 37 the last century is up to 100 times higher than the background extinction rate. This
 38 anthropogenic pressure causes habitat loss and increased competition from invasive
 39 organisms (Butchart et al., 2010), which leads to species extinction (Ceballos et al., 2015;
 40 May & Lawton, 1995), and thus has serious impacts on global biodiversity. Over the last
 41 decades, several studies have shown how human impacts affect the structure of ecosystems
 42 and how these changes can backfire and affect humans negatively with floods, fires, air
 43 pollution, heat waves, and vector-borne diseases (Bellard et al., 2012; Cardinale et al., 2012;
 44 Goberna et al., 2014; Kortsch et al., 2015; Nadeau et al., 2017; Parmesan & Yohe, 2003; Pecl
 45 et al., 2017; Woodward et al., 2010). Some species are more susceptible to extinction than
 46 others due to their traits, including: reproductive rate, habitat specialization, body size, and
 47 geographic range (Davidson et al., 2009; Fritz & Purvis, 2010). Therefore, understanding how
 48 species are going to respond in future scenarios of climate change is necessary to predict the
 49 impact of the loss of certain species on ecosystems, and it will be useful for conservation of
 50 biodiversity.

51 Until recently, evolution was thought to play no substantial role in a population's
 52 resilience when facing a rapid environmental change (Ferrière et al., 2004). The common idea
 53 was that a population in decline, exposed to a deteriorating environment, would become
 54 extinct. However, Gonzalez et al. (2012) and Bell (2013) coined and matured the idea of
 55 evolutionary rescue (ER). In an ER scenario, adaptive processes could be triggered in some
 56 resistant individuals of the population under environmental stress, allowing them to rapidly
 57 proliferate and counter the rate of decline of the population, thereby changing our perspective
 58 on communities with populations that are threatened with extinction (van Eldijk et al., 2020).

59 The most used tools to evaluate how species are dealing with climate change are
 60 ecological niche models (ENMs) (Araújo & New, 2007; Ehrlén & Morris, 2015; Elith et al.,
 61 2010; Guisan & Thuiller, 2005). ENMs use mathematical modelling of a species' relationship
 62 with environmental variables, and predict habitat suitability for that species based on known
 63 occurrence data (Araújo et al., 2011; Guisan & Thuiller, 2005). ENMs based on climate data
 64 have proven extremely useful in assessing the effectiveness of the distribution of protected
 65 areas (Catullo et al., 2008), assessing species vulnerability to local land-use changes (Santos

et al., 2013), predicting distributions of rare species (Marino et al., 2011; Rheingantz et al., 2014), and predicting possible responses to climate change by species and ecosystems (Moor et al., 2015; Sobral-Souza et al., 2018).

However, the use of ENMs with climatic variables alone has been debated in several studies (Diniz-Filho et al., 2019; Elith et al., 2010; Synes & Osborne, 2011), mainly because ENMs do not incorporate intrinsic characteristics of the populations, relying on the idea that all the mechanisms that affect species' distributions are captured by the environmental data (Diniz-Filho et al., 2019). However, niche models that use traits (morphological and physiological) or genetic data are complex and do not work well when the niches of several species are modeled simultaneously (Norberg et al., 2012).

The attempt to predict responses of species to climate change is further limited by uncertainties surrounding climatic predictions - with slight differences existing between different general circulation models (GCM) - and by uncertainties about the possibilities of measuring evolutionary rescue.

Recently, Diniz-Filho et al. (2019) applied a macroecological framework to estimate responses to evolutionary change and the likelihood of evolutionary rescue; they proposed the H value (Haldanes) to estimate the evolutionary change required by species to maintain their populations in future environmental scenarios, giving a biological and evolutionary meaning to temperature variations that species will experience. According to the framework proposed by Diniz-Filho et al. (2019), the greater the variation in temperature between present and future, the greater the H value, and consequently, the more difficult it is for the species to experience an ER scenario. Likewise, the fewer generations the species can have until the future, the higher the H . In short, the smaller the temperature difference and the larger the number of generations, the more likely it is for evolutionary rescue to happen, and for a species to persist in the face of climate change.

WWF (2018) showed an average 60% decrease in vertebrate populations, and a quarter of all known mammals are currently threatened with extinction (IUCN, 2020). Within this group, the canids (family Canidae) is an excellent group to test the impacts of climate changes on future distributions, as they are distributed in all continents, except Antarctica (Sillero-Zubiri et al., 2004; Wang & Tedford, 2008), and because as medium-large mammals they are more prone to extinction than smaller species (Rija et al., 2020). Like other species, canids are affected by the consequences of urbanization and climate change: coyotes (*Canis latrans*) and red foxes (*Vulpes Vulpes*) have been observed in urban areas in North-America (Lombardi et al., 2017; Mueller et al., 2018; Poessel et al., 2013, 2017), while the red fox has

invaded a habitat in northern Europe that was previously occupied only by the arctic fox (*Vulpes lagopus*) (WWF, 2018). Understanding how canids are affected by changes in the landscape, and being able to predict their future distributions is essential to outline conservation strategies for different species.

Here we use climate-based ENMs to: 1) model the distribution of all canids under present climate conditions, 2) predict possible changes in Canidae distribution under climate change in the next 54 years (2075), and identify species at risk of losing some or all of their current range, but also assess if some species could enlarge it; and 3) identify which species are most likely to adapt to changing climatic conditions and therefore avoid the negative effects of temperature change.

2 MATERIALS AND METHODS

2.1 Occurrence and environmental data

Species occurrence data for all canids were taken from VertNet (Constable et al., 2010) and the Global Biodiversity Information Facility (GBIF, 2020) online databases. The number of occurrence points is shown in Tables S1, and cover all the known distribution of the 36 species used here (which correspond to 100% of the living Canidae species). We spatially filtered the data using SDMToolbox 2.0 (Brown et al., 2017), in ArcGis 10.3.1 (Environmental Systems Resource Institute, 2019), to remove duplicate occurrence points. As there are different classifications for the Canidae family in relation to the number of species (Bardeleben et al., 2005; Perini et al., 2010; Zrzavy & Ricánková, 2004), here we use the most recent canid phylogeny proposed by Porto et al. (2019) to define which species of Canidae ($n = 36$ - Table S1) would be considered here to model their potential distributions.

For environmental variables, we downloaded a digital elevation model (DEM) (IUCN, 2019) and the standard 19 Worldclim bioclimatic variables for the present and future (2075) (Hijmans et al., 2005). In addition, we used the distance to freshwater as a variable, which we measured using the Natural Earth River and lake maps, and the Euclidean distance tool in ArcGis. To clarify the environmental data we masked the variables and imported them into R 4.0-2 (R Development Core Team, 2020) and tested for multicollinearity using variance inflation factor (VIF) tests with the package regclass 1.6 (Petrie, 2020) and pairwise plots. Highly correlated variables (VIF score > 10 or Pearson correlation > 0.7 respectively) were eliminated one at a time, starting with the variable(s) deemed to possess the least ecological relevance based on the VIF tests.

2.2 Ecological niche modelling

ENMs for the present were performed using the R package SDM 1.0-89 (Naimi & Araújo, 2016). To model species' niches for the present, we generated 10.000 random background points within a mask equivalent to the species' known IUCN ranges, buffered to 220 km (or approximately two decimal degrees), producing a presence-absence matrix of species within defined grids cells (pixels). We built ensembles (objects with a weighted averaging over all predictions from several fitted models) of four different models: Maxent, Support Vector Machine (SVM), Random Forest (RF), and Boosted Regression Tree (BRT). For all models, we used 90% as training data and 10% were retained as test points. Models were only accepted if they had acceptable True Skill Statistic (TSS - calculated as the sum of specificity + sensitivity - 1) and Area Under the Curve (AUC) values (0.7 being the minimum accepted AUC, 0.6 the minimum TSS (Allouche et al., 2006)). We used both TSS and AUC to evaluate the models because they assign different weights depending on the sample size of the data used (Guisan et al., 2017), and hence we believe our results to be more robust if both criteria are met.

In order to verify whether the ENMs and IUCN polygons agree, we compared the current distribution maps of all species of canids available at IUCN against the maps created here through ENMs. IUCN maps were generated by minimum convex polygons, which represent the realized niche of the species, while the ENMs here bring a more detailed notion of their fundamental niche.

We modelled the future distribution of species based on the most pessimistic climate scenario for the year 2075 (RCP 8.5 - Representative Concentration Pathway) from IPCC (2007). We chose this scenario because it seems to have become the most realistic one over the last years, and can even be under-estimating future concentrations of atmospheric carbon (Christensen et al. (2018). RCP 8.5 assumes high global CO₂ concentration, a high rate of human population growth, and an increased use of energy and land. We used an ensemble of three General Circulation Models (GCMs): Access1.0 (exhibits a high skill score with regard to historical climate), HadGEM2 (has a good representation of extreme El Niño events), and MIROC5 (also has a good representation of extreme El Niño events, and represents all RCPs scenarios well). Maps of suitability (present/future) are shown on a continuous scale to better visualize the potential distribution of species.

2.3 Evolutionary rescue calculations

H values were calculated for each of the 36 canids to predict whether they can adapt to climate change and prevent the loss of their habitat. We assumed that temperature is a representation of the species' niche (tolerance) most closely reflecting climate change. For each species, changes in maximum temperature of the warmest month (Bio05) across the entire range were estimated, and the temperature change in each cell was calculated as the average of the future temperature (in the warmest month) minus the average of the present temperature (in the warmest month). Following Diniz-Filho et al. (2019), H values were calculated using:

$$H = \frac{\frac{Y_0 - Y_t}{Y_{sd}}}{g}$$

where Y_0 is the mean temperature at the present, Y_t is the mean temperature at time t in the future, Y_{sd} is the standard deviation of the present temperature tolerance (assuming a constant variance between generations), and g is the number of generations between present and future. The generation lengths for all canid species was compiled from the Animal Diversity Web (ADW - Myers et al., 2018) and PanTHERIA (Jones et al., 2009) (Table S1). The higher the value of H , the greater the rate of evolutionary change needed for a species to experience ER, and consequently, the more difficult it is to maintain its population facing a climatic change scenario.

For the evolutionary rescue analyses, we used the threshold maps (binary) for each species, produced with the suitability maps because they show presence/absence values based on the specificity and sensitivity of the model (Liu et al., 2015).

3 RESULTS

3.1 Ecological niche modelling

All ENMs produced acceptable accuracy values for TSS and AUC. After testing highly correlated variables, only five were not excluded and were used to model canid niches, they are: distance to freshwater (DIST), the maximum temperature in the warmest month (Bio05), precipitation in the driest month (Bio14), elevation (DEM).

To check the reliability of the ENMs we compared their predictions on the present distributions with the actual current distributions according to IUCN polygons (realized niche) (Appendix - Figure S1 – S36). With the exception of a single species, *Canis lupus*, the

distribution polygons fall within the areas that the ENMs demonstrate to be suitable for the species to occupy (fundamental niche). Species richness maps for the present generated by ENMs (Figure 1) and by polygons (Figure S37) show very similar patterns of species overlap, generally maintaining the same hotspot locations in the Middle East + Northeast Africa region and western part of the USA. However, there is an exception: the richness map based on polygons shows the presence of *Canis lupus* in the Middle East region towards India, but this is not predicted by the ENMs (see Discussion). Because of the high similarity our ENM predictions seem highly reliable, and we therefore compare our future ENM predictions with ENM predictions for the present, as they are better comparable (both describe the fundamental niche).

Our models indicated that 27 species were predicted to experience range contractions under climate change, while 9 were predicted to expand in range overall (Table S2). In all three Canidae clades (wolves, foxes, and South-American canids), we find that most species will contract their ranges, and a few will expand their ranges (Figure S38A-S38C). We discuss them now in more detail.

The South-American canids (Figure S38C), *Atelocynus microtis*, *Lycalopex fulvipes*, and *Lycalopex sechurae* are predicted to see future climate suitability fall below their modelled threshold across their entire ranges (Table S2), losing a large part of their geographical distributions (Appendix - Figures S39, S40, and S41). In contrast, *Cerdocyon thous* is the only South-American canid that was predicted to have a considerable expansion in its geographical area under future conditions; moreover, the ENM predicts that *C. thous* will occupy areas within the Amazon Forest not inhabited before (Table S2, and also see Appendix - Figure S38C and Figure S42).

In the clade of wolves, *Canis latrans* and *Canis rufus* are probably going to lose a large part of their ranges in North America, while *Canis anthus* and *Canis lupus* are expected to increase their distributions, mainly in desert areas such as the Middle East, for both species, and the deserts in the USA for *C. lupus* (Table S2, and also see Appendix - Figure S38A, Figure S43, and Figure S44).

Some of the fox species are predicted to suffer severe losses in their ranges (Table S2 and Figure S38B). Among them, *Urocyon littoralis* stands out: even though it is considered an endangered species at the moment, the ENMs predicted that *U. littoralis* will lose 28.6% of its (small) current distribution (Table S2). *Vulpes chama*, *Vulpes bengalensis*, and *Vulpes velox* also were predicted to have a considerable decrease in their geographical ranges. By contrast, *Vulpes corsac*, *Vulpes vulpes*, *Otocyon megalotis*, and *Urocyon cinereoargenteus* will

probably experience range expansions under future climatic conditions. In fact, the ENM predicted that *V. vulpes* will increase 5.7% of its distribution, inhabiting new areas such as the Middle East, Northern Canada, and Greenland (Appendix - Figure S45).

The richness map of the present (Figure 1) shows that the overlap of different species is very low around the planet. The map also points to two hotspot areas for canid diversity, one in the western part of the USA (Figure 1A), and another in the Middle East + Northeast Africa region (Figure 1B). The richness map for the future (Figure 2) shows that patterns of richness are predicted to change under future climatic conditions, where the main changes will be in the hotspot areas. The USA hotspot is predicted to reduce its area considerably due to the low species overlap in the future. By contrast, The Middle East + Northeast Africa hotspot is predicted to increase in size.

The ENMs indicated species that do not overlap currently will start to overlap in their distributions, and even those that overlap in only small parts of their distributions will suffer considerable increases in their overlap areas. In South America, *C. thous* is predicted to invade areas where only *A. microtis* and *Speothos venaticus* live, inside the Amazon rainforest (Appendix - Figures S39, S42, and S46). With the great expansion of *V. vulpes*' geographical distribution, this species is expected to overlap its area with *V. bengalensis*, *Vulpes rueppellii*, and *Vulpes zerda* (Appendix - Figures S45, S47, S48, and S49). In addition, *C. lupus* will probably overlap in areas occupied before only by *V. bengalensis*, *V. rueppellii*, *V. zerda*, and *Canis aureus* (Appendix - Figures S44, S47, S48, S49, and S50).

3.2 Evolutionary rescue

Most of canids presented evolutionary rates around 0.01 Haldanes (Table S2). The highest *H* value was found for *A. microtis* (*H* = 0.047 Haldanes), and the lowest value was from *Lycalopex griseus* (*H* = 0.004 Haldanes) (Table S2).

We found a significant weak negative correlation between change in range size and evolutionary potential: species that are predicted to undergo more habitat loss according to the ENMs have a lower potential for ER, according to the *H* values (Figure 3).

4 DISCUSSION

We applied models of evolutionary rescue, using temperature and generation cycle as intrinsic characteristics of canids, together with ENMs to understand the magnitude of the effects of climate change on Canidae distribution. Predictions for the future by ENMs, derived from the

IPCC worst climate change scenario, suggested that climate change will affect canids in distinct ways, where some species will expand or maintain their distributions, while most will suffer a large reduction in their suitable areas. Furthermore, the calculated Haldanes suggest that for some species it will be more difficult to keep up with the pace of temperature changes than others. We detected a weak negative correlation between habitat loss and potential for evolutionary rescue, indicating that the species with higher potential to evolutionary rescue are the ones that gain area or lose only a small part of their future distributions, while the ones which are going to lose a large part of their future distribution will need a higher evolutionary change to maintain their populations. *Atelocynus microtis*, for example, is predicted to lose about half of its potential distribution and has the highest H value among canids ($H = 0.047$ Haldanes). This negative correlation is to be expected because larger differences between present and future temperatures will increase H and will also make it more likely that range sizes will change.

Our results suggest that global warming will be devastating to the Canidae family as a whole. However, even in this pessimistic scenario, some species have the potential to benefit from future conditions and considerably expand their geographic distributions. In general, several taxa, including mammals, birds, amphibians, and reptiles, are expected to experience drastic range reductions (Araújo & New, 2007; Diniz-filho et al., 2009; Hidasi-neto et al., 2019; Lawler et al., 2009; Maiorano et al., 2011; Peterson et al., 2002). In a scenario such as this, several communities will probably lose phylogenetic and functional diversity (Davis et al., 1998; Hidasi-neto et al., 2019), and considering the number of interactions that will be lost within these areas, the ecological impacts due to indirect effects may be stronger than the direct effects of climate change on species' distributions (Davis et al., 1998; Peterson et al., 2002). Carnivores, through population regulation, can promote the coexistence of several species by reducing interspecific competition (Paine, 1966). Because canids, being carnivores, hunt distinct animals, they end up regulating the population dynamics of their prey, which is an important factor for maintaining biodiversity (Sanders et al., 2013; Sanders & van Veen, 2012).

In South-America, there is a very concerning situation, where *A. microtis* will probably contract its range substantially and undergo fragmentation of its distribution within the Amazon Forest, while *C. thous* will expand. *A. microtis* is ecologically restricted to very specific resources and conditions (Sillero-Zubiri et al., 2004; Wilson & Mittermeier, 2009). By contrast, *C. thous* is a generalist species with a large distribution across South-America (Sillero-Zubiri et al., 2004). Currently, the status of *A. microtis* is "Near Threatened" (IUCN,

2019), but considering the climate change effects shown here, and the fact that the Amazon Forest has been suffering with wildfires and an intense deforestation process over the last decades (Exbrayat et al., 2017; INPE, 2019), *A. microtis* is probably experiencing a substantial habitat loss followed by a very likely increase in the number of direct encounters with another competitor. Thus, we suggest that its “Near Threatened” status must change, at least, to “Vulnerable”.

A similar situation applies to *V. vulpes* and *V. lagopus*. The first one has a wide distribution over the northern hemisphere, while the second is restricted to areas covered by snow around The North Pole, but both species overlap in the Tundra of North America and Eurasia (Hersteinsson & Macdonald, 1992; Sillero-Zubiri et al., 2004). Over the past few years there has been an increase in the number of encounters between the two species due to the warming temperatures that are gradually melting the Arctic ice cap, reducing the available area for *V. lagopus*, but making it possible for *V. vulpes* to expand its distribution to the north into arctic tundra in Eurasia and North America (Gallant et al., 2012). This reality is even more aggravating in the future scenario shown here, considering the large area loss by *V. lagopus* to *V. vulpes* (Figure S51). However, Gallant et al. (2012) suggested that food scarcity in these areas seems to explain the dynamics of the geographical overlap of both two species better than climate warming. Nevertheless, the effects of area loss must still be taken into account to outline conservation strategies for *V. lagopus*.

The loss of species has severe impacts on the functioning of ecosystems (Cardinale et al., 2012; Kennedy et al., 2002; Lyons & Schwartz, 2001; Pimm et al., 2014). In general, reductions in the number of species (functional groups) decrease the efficiency of communities to capture resources, and convert these into biomass (Balvanera et al., 2006; Cardinale et al., 2012; Quijas et al., 2010). Our niche models detected two major richness hotspots for Canidae: one in the Middle East + North East Africa and one in North America. The former is predicted to undergo a small expansion, mainly due to the range expansion of *C. lupus*, *C. anthus*, and *V. vulpes* over these areas, and the capacity of *C. lupus* and *V. vulpes* to live around urban areas (Sillero-Zubiri et al., 2004; Wang & Tedford, 2008; Wilson & Mittermeier, 2009). This capacity can also explain the wide distribution of both species around the world. The other hotspot area, in North America, is expected to experience a considerable area reduction. This can be explained by the small portion of this hotspot that is within protected areas in the USA, according to Brum et al. (2017).

Here, the ENMs for all canids (appendix) agreed well with the current distribution of canids, suggesting that the methodology we applied is reliable to assess the impacts of climate

change on Canidae, taking into account their main niche dimensions. *Canis lupus* is the only species for which the ENMs for the present did not encompass the entire distribution presented by its polygon, because it is not predicted to occur in the Middle East. This might be explained by the presence of a single population found in that region, which results in the distribution of the species to be extended to areas that are not suitable. The IUCN distribution maps are widely used in several studies for different purposes (Kyne et al., 2020; Porto et al., 2021; Shier, 2015; Zhang et al., 2019), and are defined as the area within the outermost limits of known occurrence for a species, but this area is not an estimate of the extent of occupied habitat, it only measures the general extension of the localities in which the species is found (Gaston & Fuller, 2009). Thus, polygons are highly susceptible to sampling biases. Nevertheless, it is important to point out that ENMs for the future suggest that *Canis lupus* will expand its distribution to the Middle East, which could be an indication that this region is already becoming suitable for the species.

Our methods assumed that the prey of the Canidae will respond to environmental changes at the same rate as their (apex or medium-level) predators. Indeed, climate change has already been observed to have wide-ranging trophic effects (Gilman et al., 2010), and physiological and behavioral effects in other species (Parmesan, 2006). Modelling the effect of climate change on species' communities and trophic interactions has proven extremely difficult, but these interactions can have serious impacts on species distributions (Sanders et al., 2013; Sanders & van Veen, 2012). These trophic interactions may be further disrupted by invasive species, the spread of which could be accelerated by climate change (Hellmann et al., 2008).

Looking at the H values, two cases are very concerning. *Atelocynus microtis* and *Chrysocyon brachyurus* present higher H values compared to other canids (0.047 and 0.027, respectively), and based on Diniz-Filho et al. (2019), these species have a lower potential for evolutionary rescue. Although H values and ENMs try to elucidate the future of species, they have distinct points of view about the effects of climate change on canids, and therefore should not be compared. However, these two approaches can shed light on Canidae responses to the future of the planet. H values suggest that some species have less potential than others to adapt fast enough to temperature changes, but ENMs indicate that some of them may increase their range, because more suitable habitats will become available for them due to climate change. Thus, in these cases ecological processes seem to prevail over evolutionary ones.

Unfortunately, very little is known about ER in nature to compare with our findings, mostly because the idea that evolution may influence the persistence of a population facing a rapid environmental change is very recent. Nevertheless, Diniz-Filho et al. (2019) already suggested that the use of the ER approach for wider geographical areas might not be that simple. They suggested that in order to obtain a standard temperature deviation, the real temperature tolerances must be known. However, no lab values were available for any wild canid, meaning that only values obtained from range estimations and ENMs could be used. Nonetheless, both may underestimate a species' true temperature tolerance. For example, while we have extracted values of mean Bio05 (maximum temperature in the warmest month), sometimes these values are well below the highest value seen within a species range.

The biogeographic patterns observed in this study may provide useful information for assessing how canids are distributed in the present over the planet, being an alternative to the distribution polygons provided by IUCN (2020). Climate change is projected to play an essential role in the geographical distribution of canids, so our predictions can be used to identify key areas for conservation strategies. This should receive special attention because as we showed, most of the Canidae hotspot regions are not located within protected areas.

DECLARATION SECTION

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

All data generated or analyzed during this study are included in this article and in the supplementary files.

Competing interests

We have no competing interests.

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Authors' contributions

L.M.V.P. and D.B. conceived and designed the study and analyses. L.M.V.P. and D.B. performed the analyses. L.M.V.P. and D. B. wrote the first draft of the manuscript. R.S.E. and R.M. commented on the methods and contributed to substantial revisions on the draft.

REFERENCES

- Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, 43(6), 1223–1232. <https://doi.org/10.1111/j.1365-2664.2006.01214.x>
- Araújo, M. B., Alagador, D., Cabeza, M., Nogués-Bravo, D., & Thuiller, W. (2011). Climate change threatens European conservation areas. *Ecology Letters*, 14(5), 484–492. <https://doi.org/10.1111/j.1461-0248.2011.01610.x>
- Araújo, M. B., & New, M. (2007). Ensemble forecasting of species distributions. *Trends in Ecology and Evolution*, 22(1), 42–47. <https://doi.org/10.1016/j.tree.2006.09.010>
- Balvanera, P., Pfisterer, A. B., Buchmann, N., He, J.-S., Nakashizuka, T., Raffaelli, D., & Bernhard, S. (2006). Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecology Letters*, 9, 1146–1156. <https://doi.org/10.1111/j.1461-0248.2006.00963.x>
- Bardeleben, C., Moore, R. L., & Wayne, R. K. (2005). A molecular phylogeny of the Canidae based on six nuclear loci. *Molecular Phylogenetics and Evolution*, 37(3), 815–831. <https://doi.org/10.1016/j.ympev.2005.07.019>
- Bell, G. (2013). Evolutionary rescue and the limits of adaptation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1610), 1–6. <https://doi.org/10.1098/rstb.2012.0080>
- Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. *Ecology Letters*, 15(4), 365–377. <https://doi.org/10.1111/j.1461-0248.2011.01736.x>
- Brown, J. L., Bennett, J. R., & French, C. M. (2017). SDMtoolbox 2.0: The next generation Python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. *PeerJ*, 2017(12). <https://doi.org/10.7717/peerj.4095>
- Brum, F. T., Graham, C. H., Costa, G. C., Hedges, S. B., Penone, C., Radeloff, V. C., Rondinini, C., Loyola, R., & Davidson, A. D. (2017). Global priorities for conservation across multiple dimensions of mammalian diversity. *Proceedings of the National Academy of Sciences of the United States of America*, 114(29), 7641–7646. <https://doi.org/10.1073/pnas.1706461114>
- Butchart, S. H. M., Walpole, M., Collen, B., Van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., Baillie, J. E. M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K. E., Carr, G. M., Chanson, J., Chenery, A. M., Csirke, J., Davidson, N. C., Dentener, F., Foster, M., Galli, A., ... Watson, R. (2010). Global biodiversity: Indicators of recent declines. *Science*, 328(5982), 1164–1168. <https://doi.org/10.1126/science.1187512>
- Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., MacE, G. M., Tilman, D., Wardle, D. A., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. S., & Naeem, S. (2012). Biodiversity loss and its impact on humanity. *Nature*, 486(7401), 59–67. <https://doi.org/10.1038/nature11148>
- Catullo, G., Masi, M., Falcucci, A., Maiorano, L., Rondinini, C., & Boitani, L. (2008). A gap analysis of Southeast Asian mammals based on habitat suitability models. *Biological Conservation*, 141(11), 2730–2744. <https://doi.org/10.1016/j.biocon.2008.08.019>
- Ceballos, G., Ehrlich, P. R., Barnosky, A. D., García, A., Pringle, R. M., & Palmer, T. M. (2015). Accelerated modern human-induced species losses: Entering the sixth mass extinction. *Science Advances*, 1(5), 9–13. <https://doi.org/10.1126/sciadv.1400253>

- 444 Christensen, P., Gillingham, K., & Nordhaus, W. (2018). Uncertainty in forecasts of long-run economic growth.
445 *Proceedings of the National Academy of Sciences*, 115(21), 5409–5414.
446 <https://doi.org/10.1073/pnas.1713628115>
- 447 Constable, H., Guralnick, R., Wiczeorek, J., Spencer, C., Peterson, A. T., Bart, H., Bates, J., Cotter, G., Hanken,
448 J., Moritz, C., Simmons, N., & Trueb, L. (2010). VertNet: A new model for biodiversity data sharing.
449 *PLoS Biology*, 8(2), 1–4. <https://doi.org/10.1371/journal.pbio.1000309>
- 450 Davidson, A. D., Hamilton, M. J., Boyer, A. G., Brown, J. H., & Ceballos, G. (2009). Multiple ecological
451 pathways to extinction in mammals. *Proceedings of the National Academy of Sciences of the United States*
452 *of America*, 106(26), 10702–10705. <https://doi.org/10.1073/pnas.0901956106>
- 453 Davis, A. J., Jenkinson, L. S., & Lawton, J. H. (1998). Making mistakes when predicting shifts in species range
454 in response to global warming. *Nature*, 391(February), 783–786.
- 455 Diniz-filho, A. F., Bini, L. M., Rangel, T. F., Loyola, R. D., Hof, C., Nogue, D., & Arau, M. B. (2009).
456 *Partitioning and mapping uncertainties in ensembles of forecasts of species turnover under climate*
457 *change. September*, 897–906. <https://doi.org/10.1111/j.1600-0587.2009.06196.x>
- 458 Diniz-Filho, J. A. F., Souza, K. S., Bini, L. M., Loyola, R., Dobrovolski, R., Rodrigues, J. F. M., Lima-Ribeiro,
459 S., Terribile, L. C., Rangel, T. F., Bione, I., Freitas, R., Machado, I. F., Rocha, T., Lorini, M. L., Vale, M.
460 M., Navas, C. A., Maciel, N. M., Villalobos, F., Olalla-Tarraga, M. A., & Gouveia, S. (2019). A
461 macroecological approach to evolutionary rescue and adaptation to climate change. *Ecography*, 42(6),
462 1124–1141. <https://doi.org/10.1111/ecog.04264>
- 463 Ehrlén, J., & Morris, W. F. (2015). Predicting changes in the distribution and abundance of species under
464 environmental change. *Ecology Letters*, 18(3), 303–314. <https://doi.org/10.1111/ele.12410>
- 465 Elith, J., Kearney, M., & Phillips, S. (2010). The art of modelling range-shifting species. *Methods in Ecology*
466 *and Evolution*, 1(4), 330–342. <https://doi.org/10.1111/j.2041-210x.2010.00036.x>
- 467 ESRI (Environmental Systems Resource Institute). (2019). *ArcGIS Desktop Help 10.2. Geostatistical Analyst*.
468 <https://www.esri.com/en-us/home>
- 469 Exbrayat, J., Liu, Y. Y., & Williams, M. (2017). Impact of deforestation and climate on the Amazon Basin ' s
470 above- ground biomass during 1993 – 2012. *Scientific Reports*, 7, 1–7. [https://doi.org/10.1038/s41598-](https://doi.org/10.1038/s41598-017-15788-6)
471 [017-15788-6](https://doi.org/10.1038/s41598-017-15788-6)
- 472 Ferrière, R., Dieckmann, U., & Couvet, D. (2004). *Evolutionary Conservation Biology*. Cambridge University
473 Press.
- 474 Fritz, S. A., & Purvis, A. (2010). Selectivity in Mammalian Extinction Risk and Threat Types: a New Measure
475 of Phylogenetic Signal Strength in Binary Traits. *Conservation Biology*, 24(4), 1042–1051.
- 476 Gallant, D., Canada, P., Slough, B. G., Reid, D. G., Society, W. C., & Berteaux, D. (2012). *Arctic fox versus red*
477 *fox in the warming Arctic□: four decades of den surveys in north Yukon. May 2014*.
478 <https://doi.org/10.1007/s00300-012-1181-8>
- 479 Gaston, K. J., & Fuller, R. A. (2009). The sizes of species' geographic ranges. *Journal of Applied Ecology*,
480 46(1), 1–9. <https://doi.org/10.1111/j.1365-2664.2008.01596.x>
- 481 GBIF. (2020). *GBIF*. <https://www.gbif.org/>
- 482 Gilman, S. E., Urban, M. C., Tewksbury, J., Gilchrist, G. W., & Holt, R. D. (2010). A framework for community
483 interactions under climate change. *Trends in Ecology and Evolution*, 25(6), 325–331.
484 <https://doi.org/10.1016/j.tree.2010.03.002>
- 485 Goberna, M., Navarro-Cano, J. A., Valiente-Banuet, A., García, C., & Verdú, M. (2014). Abiotic stress tolerance
486 and competition-related traits underlie phylogenetic clustering in soil bacterial communities. *Ecology*
487 *Letters*, 17(10), 1191–1201. <https://doi.org/10.1111/ele.12341>
- 488 Gonzalez, A., Ronce, O., Ferriere, R., & Hochberg, M. E. (2012). Evolutionary rescue: An emerging focus at the
489 intersection between ecology and evolution. *Philosophical Transactions of the Royal Society B: Biological*
490 *Sciences*, 368(1610), 8. <https://doi.org/10.1098/rstb.2012.0404>
- 491 Guisan, A., & Thuiller, W. (2005). Predicting species distribution: Offering more than simple habitat models.

492 *Ecology Letters*, 8(9), 993–1009. <https://doi.org/10.1111/j.1461-0248.2005.00792.x>

493 Guisan, A., Thuiller, W., & Zimmermann, N. (2017). *Habitat Suitability and Distribution Models: with*
494 *Applications in R*. Cambridge University Press. <https://doi.org/10.1017/9781139028271>

495 Hellmann, J. J., Byers, J. E., Bierwagen, B. G., & Dukes, J. S. (2008). Five potential consequences of climate
496 change for invasive species. *Conservation Biology*, 22(3), 534–543. [https://doi.org/10.1111/j.1523-](https://doi.org/10.1111/j.1523-1739.2008.00951.x)
497 1739.2008.00951.x

498 Hersteinsson, P., & Macdonald, D. W. (1992). Interspecific Competition and the Geographical Distribution of
499 Red and Arctic Foxes *Vulpes Vulpes* and *Alopex lagopus*. *Oikos*, 64(3), 505–515.

500 Hidasi-neto, J., Caroline, D., Resende, F., Macedo, L. De, Valtuille, F., Dias, R., & Vinicius, M. (2019). Climate
501 change will drive mammal species loss and biotic homogenization in the Cerrado Biodiversity Hotspot.
502 *Perspectives in Ecology and Conservation*, 17(2), 57–63. <https://doi.org/10.1016/j.pecon.2019.02.001>

503 Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005). Very high resolution interpolated
504 climate surfaces for global land areas. *International Journal of Climatology*, 25(15), 1965–1978.
505 <https://doi.org/10.1002/joc.1276>

506 INPE. (2019). *INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS*. <http://terrabrasilis.dpi.inpe.br/downloads/>

507 IPCC. (2007). *Climate change the physical science basis. Contribution of Working Group I to the Fourth*
508 *Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

509 IUCN. (2019). *The IUCN Red List of Threatened Species. Version 2019-2*. <http://www.iucnredlist.org>

510 IUCN. (2020). *The IUCN Red List of Threatened Species*.

511 Jones, K. E., Bielby, J., Cardillo, M., Fritz, S. A., O'Dell, J., Orme, C. D. L., Safi, K., Sechrest, W., Boakes, E.
512 H., Carbone, C., Connolly, C., Cutts, M. J., Foster, J. K., Grenyer, R., Habib, M., Plaster, C. A., Price, S.
513 A., Rigby, E. A., Rist, J., ... Purvis, A. (2009). PanTHERIA: a species-level database of life history,
514 ecology, and geography of extant and recently extinct mammals. *Ecology*, 90(9), 2648–2648.
515 <https://doi.org/10.1890/08-1494.1>

516 Kennedy, T. A., Naeem, S., Howe, K. M., Knops, J. M. H., Tilman, D., & Reich, P. (2002). Biodiversity as a
517 barrier to ecological invasion Biodiversity as a barrier to ecological invasion. *Nature*, 417, 10–13.
518 <https://doi.org/10.1038/nature00776>

519 Kortsch, S., Primicerio, R., Fossheim, M., Dolgov, A. V., & Aschan, M. (2015). Climate change alters the
520 structure of arctic marine food webs due to poleward shifts of boreal generalists. *Proceedings of the Royal*
521 *Society B: Biological Sciences*, 282, 9.

522 Kyne, P. M., Jabado, R. W., Rigby, C. L., Dharmadi, Gore, M. A., Pollock, C. M., Herman, K. B., Cheok, J.,
523 Ebert, D. A., Simpfendorfer, C. A., & Dulvy, N. K. (2020). The thin edge of the wedge: Extremely high
524 extinction risk in wedgefishes and giant guitarfishes. *Aquatic Conservation: Marine and Freshwater*
525 *Ecosystems*, 30(7), 1337–1361. <https://doi.org/10.1002/aqc.3331>

526 Lawler, J. J., Shafer, S. L., White, D., Kareiva, P., Maurer, E. P., Blaustein, A. R., & Bartlein, P. J. (2009).
527 Projected climate-induced faunal change in the Western Hemisphere. *Ecology*, 90(3), 588–597.

528 Liu, C., Newell, G., & White, M. (2015). On the selection of thresholds for predicting species occurrence with
529 presence-only data. *Ecology and Evolution*, 6(1), 337–348. <https://doi.org/10.1002/ece3.1878>

530 Lombardi, J. V., Comer, C. E., Scognamiglio, D. G., & Conway, W. C. (2017). Coyote, fox, and bobcat response
531 to anthropogenic and natural landscape features in a small urban area. *Urban Ecosystems*, 20(6), 1239–
532 1248. <https://doi.org/10.1007/s11252-017-0676-z>

533 Lyons, K. G., & Schwartz, M. W. (2001). Rare species loss alters ecosystem function $\pm$ invasion resistance.
534 *Ecology Letters*, 4, 358–365.

535 Maiorano, L., Falcucci, A., Zimmermann, N. E., Psomas, A., Pottier, J., Baisero, D., Rondinini, C., Guisan, A.,
536 & Boitani, L. (2011). The future of terrestrial mammals in the Mediterranean basin under climate change.
537 *Philosophical Transactions of the Royal Society B*, 366, 2681–2692.
538 <https://doi.org/10.1098/rstb.2011.0121>

Marino, J., Bennett, M., Cossios, D., Iriarte, A., Lucherini, M., Plischoff, P., Sillero-Zubiri, C., Villalba, L., & Walker, S. (2011). Bioclimatic constraints to Andean cat distribution: A modelling application for rare species. *Diversity and Distributions*, 17(2), 311–322. <https://doi.org/10.1111/j.1472-4642.2011.00744.x>

May, R. M., & Lawton, J. H. (1995). Assessing extinction rates. In R. M. May & J. H. Lawton (Eds.), *Extinction Rates* (pp. 1–24). Oxford University Press.

Moor, H., Hylander, K., & Norberg, J. (2015). Predicting climate change effects on wetland ecosystem services using species distribution modeling and plant functional traits. *Ambio*, 44(1), 113–126. <https://doi.org/10.1007/s13280-014-0593-9>

Mueller, M. A., Drake, D., & Allen, M. L. (2018). Coexistence of coyotes (*Canis latrans*) and red foxes (*Vulpes vulpes*) in an urban landscape. *PLoS ONE*, 13(1), 19.

Myers, P., Espinosa, R., Parr, C. S., Jones, T., Hammond, G. S., & Dewey, T. A. (2018). *The Animal Diversity Web*.

Nadeau, C. P., Urban, M. C., & Bridle, J. R. (2017). Coarse climate change projections for species living in a fine-scaled world. *Global Change Biology*, 23(1), 12–24. <https://doi.org/10.1111/gcb.13475>

Naimi, B., & Araújo, M. B. (2016). sdm: a reproducible and extensible R platform for species distribution modelling. *Ecography*, 29, 368–375. <https://doi.org/10.1111/ecog.01881>

Norberg, J., Urban, M. C., Vellend, M., Klausmeier, C. A., & Loeuille, N. (2012). Eco-evolutionary responses of biodiversity to climate change. *Nature Climate Change*, 2(10), 747–751. <https://doi.org/10.1038/nclimate1588>

Paine, R. T. (1966). Food Web Complexity and Species Diversity. *The American Naturalist*, 100(910), 65–75.

Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics*, 37, 637–669. <https://doi.org/10.1146/annurev.ecolsys.37.091305.110100>

Parmesan, C., & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421, 37–42.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., ... Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, 355(6332). <https://doi.org/10.1126/science.aai9214>

Perini, F. A., Russo, C. A. M., & Schrago, C. G. (2010). The evolution of South American endemic canids: A history of rapid diversification and morphological parallelism. *Journal of Evolutionary Biology*, 23(2), 311–322. <https://doi.org/10.1111/j.1420-9101.2009.01901.x>

Peterson, A. T., Ortega-huerta, M. A., Bartley, J., Sa, V., & Stockwell, D. R. B. (2002). Future projections for Mexican faunas under global climate change scenarios. *Nature*, 416(April), 164–166.

Petrie, A. (2020). *R package regclass* (1.6). <https://www.rdocumentation.org/packages/regclass/versions/1.6>

Pimm, S. L., Jenkins, C. N., Abell, R., Brooks, T. M., Gittleman, J. L., Joppa, L. N., Raven, P. H., Roberts, C. M., & Sexton, J. O. (2014). The biodiversity of species and their rates of extinction, distribution, and protection. *Science*, 344(6187), 987–997. <https://doi.org/10.1126/science.1246752>

Pitchers, W., Wolf, J. B., Tregenza, T., Hunt, J., Dworkin, I., & Hunt, J. (2014). Evolutionary rates for multivariate traits: the role of selection and genetic variation. *Philosophical Transactions of the Royal Society B*, 19(369), 13. <https://doi.org/10.5061/dryad.g4t8c>

Poessel, S. A., Breck, S. W., Teel, T. L., Shwiff, S., Crooks, K. R., & Angeloni, L. (2013). Patterns of human–coyote conflicts in the Denver Metropolitan Area. *The Journal of Wildlife Management*, 77, 297–305.

Poessel, S. A., Gese, E. M., & Young, J. K. (2017). Environmental factors influencing the occurrence of coyotes and conflicts in urban areas. *Landscape and Urban Planning*, 157, 259–269. <https://doi.org/10.1016/j.landurbplan.2016.05.022>

- 586 Porto, L. M. Vi., Maestri, R., & Duarte, L. D. S. (2019). Evolutionary relationships among life-history traits in
587 Caninae (Mammalia: Carnivora). *Biological Journal of the Linnean Society*, 128(2), 311–322.
- 588 Porto, Lucas M.V., Etienne, R. S., & Maestri, R. (2021). Explosive diversification following continental
589 colonizations by canids. *Preprint: Doi: <https://doi.org/10.1101/2021.01.08.425986>*.
- 590 Quijas, S., Schmid, B., & Balvanera, P. (2010). Plant diversity enhances provision of ecosystem services: A
591 new synthesis. *Basic and Applied Ecology*, 11(7), 582–593. <https://doi.org/10.1016/j.baae.2010.06.009>
- 592 R Development Core Team. (2020). *R: A Language and Environment for Statistical Computing*. R Foundation
593 for Statistical Computing. Vienna, Austria. (4.0.2).
- 594 Rheingantz, M. L., de Menezes, J. F. S., & de Thoisy, B. (2014). Defining Neotropical otter *Lontra longicaudis*
595 distribution, conservation priorities and ecological frontiers. *Tropical Conservation Science*, 7(2), 214–
596 229. <https://doi.org/10.1177/194008291400700204>
- 597 Rija, A. A., Critchlow, R., Thomas, C. D., & Beale, C. M. (2020). Global extent and drivers of mammal
598 population declines in protected areas under illegal hunting pressure. *PLOS ONE*, 15(8), e0227163.
599 <https://doi.org/10.1371/journal.pone.0227163>
- 600 Sanders, D., Sutter, L., & van Veen, F. J. F. (2013). The loss of indirect interactions leads to cascading
601 extinctions of carnivores. *Ecology Letters*, 16(5), 664–669. <https://doi.org/10.1111/ele.12096>
- 602 Sanders, D., & van Veen, F. J. F. (2012). Indirect commensalism promotes persistence of secondary consumer
603 species. *Biology Letters*, 8, 960–963.
- 604 Santos, H., Rodrigues, L., Jones, G., & Rebelo, H. (2013). Using species distribution modelling to predict bat
605 fatality risk at wind farms. *Biological Conservation*, 157, 178–186.
606 <https://doi.org/10.1016/j.biocon.2012.06.017>
- 607 Shier, D. M. (2015). Developing a standard for evaluating reintroduction success using IUCN Red List indices.
608 *Animal Conservation*, 18(5), 411–412. <https://doi.org/10.1111/acv.12242>
- 609 Sillero-Zubiri, C., Hoffmann, M., & Macdonald, D. (2004). *Canids: Foxes, Wolves, Jackals and Dogs*.
610 Information Press, Oxford.
- 611 Sobral-Souza, T., Vancine, M. H., Ribeiro, M. C., & Lima-Ribeiro, M. S. (2018). Efficiency of protected areas
612 in Amazon and Atlantic Forest conservation: A spatio-temporal view. *Acta Oecologica*, 87(July 2017), 1–
613 7. <https://doi.org/10.1016/j.actao.2018.01.001>
- 614 Synes, N. W., & Osborne, P. E. (2011). Choice of predictor variables as a source of uncertainty in continental-
615 scale species distribution modelling under climate change. *Global Ecology and Biogeography*, 20(6), 904–
616 914. <https://doi.org/10.1111/j.1466-8238.2010.00635.x>
- 617 van Eldijk, T. J. B., Bisschop, K., & Etienne, R. S. (2020). Uniting Community Ecology and Evolutionary
618 Rescue Theory: Community-Wide Rescue Leads to a Rapid Loss of Rare Species. *Frontiers in Ecology
619 and Evolution*, 8. <https://doi.org/10.3389/fevo.2020.552268>
- 620 Wang, X., & Tedford, R. (2008). *Dogs: Their Fossil Relatives and Evolutionary History*. (1st ed.). Columbia
621 University Press.
- 622 Wilson, E., & Mittermeier, A. (2009). *Handbook of Mammals of the World: Carnivores*. Lynx Edicions.
- 623 Woodward, G., Perkins, D. M., & Brown, L. E. (2010). Climate change and freshwater ecosystems: Impacts
624 across multiple levels of organization. *Philosophical Transactions of the Royal Society B: Biological
625 Sciences*, 365(1549), 2093–2106. <https://doi.org/10.1098/rstb.2010.0055>
- 626 WWF. (2018). *Living Planet Report - 2018: Aiming Higher*. (M. Grooten & R. E. A. Almond (eds.)). WWF.
- 627 Zhang, L., Ameca, E. I., Cowlishaw, G., Pettorelli, N., Foden, W., & Mace, G. M. (2019). Global assessment of
628 primate vulnerability to extreme climatic events. *Nature Climate Change*, 9(7), 554–561.
629 <https://doi.org/10.1038/s41558-019-0508-7>
- 630 Zrzavy, J., & Ríčanová, V. (2004). Phylogeny of Recent Canidae (Mammalia, Carnivora): relative reliability
631 and utility of morphological and molecular datasets. *Zoologica Scripta*, 33(4), 311–333.

FIGURE LIST

FIGURE 1 Species richness map of Canidae for the present produced by ENM. The richest areas (hotspots) were identified in the Middle East + Northeast Africa region (A) and western part of the USA (B). The legend on the left shows the number of overlapping species.

FIGURE 2 Species richness map of Canidae under future climate conditions produced by ENM. The richest areas (hotspots) were identified in the Middle East + Northeast Africa region (A) and western part of the USA (B). The legend on the left shows the number of overlapping species.

FIGURE 3 Plot representing the relationship between the percentage of area gained or lost by canids in relation to H values. The higher the H value, the lower the likelihood of evolutionary rescue. Red, green, and blue dots are species from the clades of foxes, South-American canids, and wolves, respectively. $R^2 = -0.187$ ($P < 0.05$).

664 SUPPLEMENTARY TEXT: TABLE LIST

665 **TABLE S1** List of the 36 species of Canidae included in our study. Age of sexual maturity of
 666 females (years), the number of generations until 2075, the number of occurrence points for each
 667 species, and the source of the original description are indicated here.

Species	Sexual maturity of females	Number of generations	Number of occurrence points	Descriptor
<i>Canis adustus</i>	0.75	100	1.028	Sundevall, 1847
<i>Canis aureus</i>	1	75	2.769	Linnaeus, 1758
<i>Canis anthus</i>	1	75	1.536	Cuvier, 1820
<i>Canis lupus</i>	2.5	25	8.490	Linnaeus, 1758
<i>Canis latrans</i>	0.84	89.3	2.402	Say, 1823
<i>Canis mesomelas</i>	0.84	89.3	645	Schreber, 1775
<i>Canis rufus</i>	1	75	30	Audubon & Bachman, 1851
<i>Canis simensis</i>	2	37.5	12	Rüppell, 1840
<i>Cuon alpinus</i>	1	75	507	Pallas, 1811
<i>Lycaon pictus</i>	1.23	60.4	281	Temminck, 1820
<i>Nyctereutes procyonoides</i>	0.82	91.5	846	Gray, 1834
<i>Vulpes bengalensis</i>	1.5	50	327	Shaw, 1800
<i>Vulpes cana</i>	0.82	91.5	396	Blanford, 1877
<i>Vulpes chama</i>	0.75	100	229	A. Smith, 1833
<i>Vulpes corsac</i>	1.38	54.3	1.193	Linnaeus, 1768
<i>Vulpes ferrilata</i>	1.15	65.2	264	Hodgson, 1842
<i>Vulpes macrotis</i>	0.82	91.5	229	Merriam, 1888
<i>Vulpes pallida</i>	1	75	406	Cretzschmar, 1826
<i>Vulpes rueppellii</i>	1	75	1.299	Schinz, 1825
<i>Vulpes velox</i>	1	75	88	Say, 1823
<i>Vulpes vulpes</i>	0.83	90.4	9.457	Linnaeus, 1758
<i>Vulpes zerda</i>	0.49	153.1	850	Zimmermann, 1780
<i>Vulpes lagopus</i>	0.83	90.4	3.468	Linnaeus, 1758
<i>Urocyon cinereoargenteus</i>	0.95	78.7	1.089	Schreber, 1775
<i>Urocyon littoralis</i>	1	75	30	Baird, 1857
<i>Otocyon megalotis</i>	0.61	122.6	515	Desmarest, 1822
<i>Atelocynus microtis</i>	1	75	238	Sclater, 1883
<i>Cerdocyon thous</i>	0.76	98.7	864	Linnaeus, 1766
<i>Chrysocyon brachyurus</i>	2	37.5	457	Illiger, 1815
<i>Lycalopex culpaeus</i>	1	75	345	Molina, 1782
<i>Lycalopex fulvipes</i>	1	75	8	Martin, 1837
<i>Lycalopex griseus</i>	1	75	255	Gray, 1837
<i>Lycalopex gymnocercus</i>	1	75	312	G. Fischer, 1814
<i>Lycalopex sechurae</i>	1	75	24	Thomas, 1900
<i>Lycalopex vetulus</i>	1	75	183	Lund, 1842
<i>Speothos venaticus</i>	0.83	90.4	1.076	Lund, 1842

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669 **TABLE S2** Area difference in species distributions for present and future, showing expansion
670 or retraction of canids' geographical distributions. *H* values are also indicated.

Species	Present area (Km ²)	Future area (Km ²)	<i>H</i>
<i>Atelocynus microtis</i>	4.379.627	2.438.970	0,047520
<i>Canis anthus</i>	15.472.384	17.583.018	0,013342
<i>Canis aureus</i>	3.448.559	3.187.594	0,008698
<i>Canis latrans</i>	12.065.866	8.749.988	0,006891
<i>Canis lupus</i>	55.058.863	57.577.546	0,02551
<i>Canis mesomelas</i>	7.840.423	6.214.900	0,009592
<i>Canis rufus</i>	1.858.413	1.529.932	0,012079
<i>Canis simensis</i>	6.707.343	6.227.124	0,012671
<i>Canis adustus</i>	12.577.073	11.623.101	0,011225
<i>Cerdocyon thous</i>	7.224.726	10.225.538	0,011357
<i>Chrysocyon brachyurus</i>	5.202.737	4.755.462	0,027895
<i>Cuon alpinus</i>	7.757.856	6.803.830	0,004926
<i>Lycalopex culpaeus</i>	3.121.231	2.923.795	0,006086
<i>Lycalopex fulvipes</i>	126.236	98.762	0,009984
<i>Lycalopex vetulus</i>	2.539.881	2.040.550	0,012808
<i>Lycalopex griseus</i>	2.961.540	2.903.216	0,004344
<i>Lycalopex gymnocercus</i>	3.354.884	2.561.320	0,005269
<i>Lycalopex sechurae</i>	2.514.432	1.209.669	0,006207
<i>Lycaon pictus</i>	8.445.869	7.276.908	0,014579
<i>Nyctereutes procyonoides</i>	7.413.459	6.018.161	0,006262
<i>Otocyon megalotis</i>	8.251.366	8.676.914	0,007170
<i>Speothos venaticus</i>	11.953.879	11.185.765	0,016549
<i>Urocyon cinereoargenteus</i>	8.757.468	9.595.434	0,011490
<i>Urocyon littoralis</i>	200.615	143.194	0,011346
<i>Vulpes bengalensis</i>	3.053.463	2.287.423	0,014108
<i>Vulpes cana</i>	6.315.447	5.439.834	0,005072
<i>Vulpes chama</i>	3.594.029	2.487.370	0,008272
<i>Vulpes corsac</i>	13.114.501	14.423.740	0,012275
<i>Vulpes ferrilata</i>	3.502.426	3.977.712	0,008895
<i>Vulpes lagopus</i>	13.405.437	12.101.093	0,004969
<i>Vulpes macrotis</i>	2.651.764	2.171.680	0,011933
<i>Vulpes pallida</i>	5.164.447	4.518.576	0,023281
<i>Vulpes velox</i>	1.360.294	1.016.829	0,022411
<i>Vulpes vulpes</i>	64.415.599	68.080.936	0,005214
<i>Vulpes zerda</i>	11.242.325	12.574.885	0,007949
<i>Vulpes rueppellii</i>	14.074.266	13.588.853	0,013633

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SUPPLEMENTARY TEXT: FIGURE LIST

FIGURE S38 Plot representation, on logarithmic scale, of range expansion or contraction over time for the clades of wolves (A), foxes (B), and South American canids (C). *H* values for each species are indicated next to each species name.

FIGURE S51 Comparison of present and future suitable areas of *Vulpes vulpes* (A) and *Vulpes lagopus* (B). The image shows regions where loss is expected to occur (red) and regions where the species will increase their distributions (blue).