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Correlates of extinction risk dynamics of mammals

Claudia Fornarini[1] | **Craig Hilton-Taylor**[2] | **Mike Hoffmann**[3] | **Rosalind J. Kennerley**[4,5] | **David L. Waldien**[6,7,8,9,10,11] | **Gill T. Braulik**[12,13] | **Leandro Jerusalinsky**[14,15] | **Gianna Minton**[13,16] | **Randall R. Reeves**[13,17] | **Elizabeth A. Williamson**[15,18] | **Carlo Rondinini**[1]

[1]Global Mammal Assessment Program, "Charles Darwin" Department of Biology and Biotechnologies, Sapienza University of Rome, Rome, Italy

[2]Biodiversity Assessment and Knowledge Team, IUCN, Cambridge, UK

[3]Conservation and Policy, Zoological Society of London, London, UK

[4]Durrell Wildlife Conservation Trust, Jersey, UK

[5]IUCN SSC Small Mammal Specialist Group, Gland, Switzerland

[6]Biological and Physical Sciences, Frederick Community College, Frederick, Maryland, USA

[7]Biology, College of William & Mary, Williamsburg, Virginia, USA

[8]Biology, Chemistry, and Environmental Science, Christopher Newport University, Newport News, Virginia, USA

[9]Lubee Bat Conservancy, Gainesville, Florida, USA

[10]Conservation group, Harrison Institute, Sevenoaks, UK

[11]IUCN SSC Bat Specialist Group, Gland, Switzerland

[12]Sea Mammal Research Unit, University of St Andrews, St Andrews, UK

[13]IUCN SSC Cetacean Specialist Group, Gland, Switzerland

[14]National Center for Research and Conservation of Primates and Xenarthrans, Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio/CPB), Brasília, Brazil

[15]IUCN SSC Primate Specialist Group, Gland, Switzerland

[16]IUCN Megaptera Marine Conservation, Wassenaar, The Netherlands

[17]Okapi Wildlife Associates, Hudson, Quebec, Canada

[18]Faculty of Natural Sciences, University of Stirling, Stirling, UK

Correspondence
Claudia Fornarini, Global Mammal Assessment Program, "Charles Darwin" Department of Biology and Biotechnologies, Sapienza University of Rome, Viale dell'Università 32, 00185 Rome, Italy.
Email: claudia.fornarini@uniroma1.it

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Abstract

Mammals continue to face increasing extinction risk, largely driven by escalating human pressures. However, the drivers of change in extinction risk remain poorly understood. We used an ordinal modeling framework (cumulative link mixed models) to test the correlation between biological traits, ecological characteristics, anthropogenic threats, and trends over time to analyze changes in extinction risk for 4,992 mammal species assessed by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. Since 1996, most species remained stable, but extinction risk increased by ~9% and decreased for <1% of the mammals. Increases in extinction risk were most pronounced in the Indomalayan, Afrotropical, and Australasian realms and in several taxonomic groups, particularly Primates. Changes were strongly structured at the genus level, indicating shared trends among related taxa. Near threatened species had the highest probability of deterioration in conservation status (9.3%), highlighting this category as a critical early-warning stage. Exposure to a very high number of threats was the strongest predictor of deterioration in

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conservation status; conversely, species benefiting from multiple conservation actions were more likely to improve than deteriorate in status, suggesting that targeted interventions may contribute to reducing extinction risk. Habitat generalists also showed greater chances of improvement. Most intrinsic traits showed limited influence on category change, except for trophic level, with generalist feeders less at risk. Overall, our results showed that mammal extinction trajectories are primarily shaped by the number of threats a species faces and its biogeographic context, emphasizing the need for a considerable scaling-up of conservation efforts, including for species that have not yet reached the highest categories of threat.

KEYWORDS
CLMMs, conservation actions, conservation status, Red List, threats

INTRODUCTION

Over the past century, biodiversity has been increasingly affected by anthropogenic pressures, including habitat loss, overexploitation, climate change, and pollution (Tittensor et al., 2014). In the last four decades, many species have experienced widespread declines in abundance leading to significant increases in extinction risk (Hoffmann et al., 2010; Pimm et al., 2014). The ongoing global biodiversity crisis underscores the urgent need to monitor biodiversity change over time; track progress toward the achievement of global conservation goals, such as those set by the Kunming–Montreal Global Biodiversity Framework of the Convention on Biological Diversity (Affinito et al., 2025; CBD, 2022); and inform coordinated future action.

Identifying the main predictors of change in extinction risk is critical for understanding the drivers of biodiversity loss (Pacifici et al., 2017; Tilman et al., 2017) and informing effective conservation policies and strategies (IPBES, 2019). Examining the direction of change can support the prioritization of interventions by anticipating which species, or species groups, are likely to experience a deterioration in conservation status in the future (Cardillo et al., 2005; Davidson et al., 2009). Furthermore, quantifying the relative importance of biological, ecological, and anthropogenic factors can provide mechanistic insights into extinction trends and guide the development of predictive models for adaptive management (Henriques et al., 2020).

According to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, approximately 27% of mammal species are threatened with extinction, highlighting the urgency of targeted conservation efforts (IUCN Standards and Petitions Committee, 2024). Anthropogenic pressures, such as habitat loss and overexploitation, strongly influence extinction trajectories, whereas conservation actions can mitigate or even reverse these effects (Hoffmann et al., 2010; Maxwell et al., 2016; Schipper et al., 2008). The impact of these pressures is particularly pronounced in tropical regions, which concentrate most of the world's endemic species and are disproportionately affected by habitat loss and degradation (Myers et al., 2000). Large-bodied species with slow reproductive rates tend to be more vulnerable to population decline, whereas species with very specific habitat requirements are less able to adapt to environmental change (Cardillo et al., 2005; Purvis et al., 2000). Cardillo et al. (2005) demonstrated that the impact of both intrinsic life-history traits and external environmental pressures on mammals increases sharply above a body mass threshold of 3 kg. Di Marco et al. (2015) retrospectively analyzed Red List transitions for a subset of 497 species between 1975 and 2013 to classify taxa as moving toward higher or lower risk, based on biological traits, anthropogenic pressures, and protected area coverage. Similarly, Davidson et al. (2012) modeled extinction risk in marine mammals, incorporating both intrinsic and extrinsic traits to predict risk levels for species listed as data deficient (DD) by the IUCN Red List, identifying several DD species as likely threatened. They also further expanded these efforts (Davidson et al., 2017) to identify regions and traits associated with extinction risk. These approaches have been valuable for identifying correlates of threat and geographic patterns of risk, but they generally used static Red List categories or forecasted future threats or had limited taxonomic and temporal scopes.

In this study, we analyzed the change in extinction risk between 1996 and the most recently published assessment of 4,992 data-sufficient mammal species on the IUCN Red List (v. 2025-1). We hypothesized that changes in species' extinction risk over time would depend on a combination of four broad classes of predictors: exposure to extrinsic pressures, including the initial extinction risk category, the number of threats and habitat types associated with each species, the natural system, and the biogeographic realm; intrinsic vulnerability, represented by the taxonomic order and genus, adult body mass, litter size, trophic level, diet breadth, and activity cycle (i.e., the temporal niche of a species); conservation actions, quantified as the number of actions implemented for each species; and temporal covariate represented by time since baseline (i.e., the time elapsed between 1996 and the most recent assessment). Based on these, we derived the following testable predictions. We predicted that species currently listed as critically endangered would show the lowest probability of deterioration in status, as they receive more targeted conservation attention than nonthreatened species. Species exposed to a higher number of threats were predicted to have a greater probability of deterioration in status, whereas species associated with a higher number of habitat types, or benefiting from a higher number of conservation actions, would show a lower probability of deterioration and a higher probability of improvement in status. Species

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occurring in tropical regions were predicted to show higher rates of deterioration in status, reflecting the concentrations of endemic species undergoing exceptional loss of habitat (Myers et al., 2000). Regarding intrinsic vulnerability, we predicted that species with larger body masses and slower reproductive rates (smaller litter size) would be more likely to experience a deterioration in conservation status, given their well-documented sensitivity to overexploitation (Cardillo et al., 2005). Finally, we predicted that species with a longer assessment interval (i.e., those not reassessed for more years since 1996) would show a higher probability of deterioration in status, as ongoing declines are more likely to have accumulated and crossed Red List thresholds over a longer period (Rondinini et al., 2014).

MATERIAL AND METHODS

Data

We collected information on taxonomy (order, family, genus, and species), extinction risk (categories from 1996 to the most recent published assessment), threats, and conservation actions for all mammal species (6,050) listed on the IUCN Red List, version 2026-1, restricted to species with an assessment published before 2026. The IUCN classification of threats and conservation actions includes three levels of detail. In this study, we considered the first-level threats and the second-level conservation actions. We also recorded biogeographic realms (Afrotropical, Antarctic, Australasian, Nearctic, Palearctic, Neotropical, Indomalayan, and Oceanic), ecological systems (terrestrial, freshwater, and marine), and second-level habitat types, including both suitable and marginal habitats. All data were downloaded from the IUCN Red List of Threatened Species (https://www.iucnredlist.org/), version 2025-1, accessed on 16 March 2025 and updated on 25 June 2026, and we used version 2026-1 to incorporate species with an assessment published up to the end of 2025. To account for intrinsic vulnerability to extinction risk, we included a set of biological traits from COalesced Mammal dataBase of INtrinsic and Extrinsic (COMBINE) traits (Soria et al., 2021), which integrates data from PanTHERIA (Jones et al., 2009), AnAge (Magalhães & Costa, 2009), EltonTraits (Wilman et al., 2014), PHYLACINE (Faurby et al., 2018), Amniotes (Myhrvold et al., 2015), and the IUCN Red List version 2020-2: adult body mass, litter size, diet breadth, trophic level, and activity cycle (i.e., the temporal niche of a species).

At the global scale, the Red List identifies eight extinction risk categories. One of these is DD, which is assigned to species when available information is insufficient to conduct an assessment. Of the remaining categories, two apply to species that are not threatened (least concern [LC] and near threatened [NT]); three designate threatened species (vulnerable [VU], endangered [EN], and critically endangered [CR]), and assignment to these categories follows the IUCN Red List criteria; and two identify extinct species (extinct in the wild [EW] and extinct [EX]). A special flag, possibly extinct (PE), applies to CR species that may be extinct, but for which some reasonable doubt exists. We excluded 774 DD and 199 species still marked as in need of updating on the Red List (i.e., those that were not reassessed after 2014) from the analysis.

The resulting dataset included 5,077 mammal species, 2,464 of which exhibited a category change. Each change was classified as either genuine—driven by increasing or emerging threats or by the beneficial impact of conservation actions—or nongenuine, that is, a result of improved knowledge, revised taxonomy, or changes in assessment methodology. For nongenuine changes, we performed backcasting, whereby the 1996 Red List categories were retrospectively corrected using current information and taxonomy (following established methodologies and protocols; Appendix S1). Mammals were also comprehensively assessed in 2008, and we applied backcasting to this assessment for consistency. However, we focused our analyses on changes between the first (1996) and the most recent assessments to quantify net long-term shifts in extinction risk.

Model specification

We used the direction of change in extinction risk (i.e., improvement, stability, and deterioration in status) as the response variable to evaluate changes in extinction risk between 1996 and the most recent published assessment. The most recent assessments ranged from 2015 to 2025, with a median gap of 20 years, an interquartile range (IQR) of 20–22 years (i.e., 50% of last reassessments occurred between 2016 and 2018), and a full range of 19–29 years from 1996. We fit a cumulative link mixed model (CLMM) using the R software version 4.5.1 (R Core Team, 2025) with the package ordinal (Christensen, 2023). The model was fit using a logit link function and the Laplace approximation for maximum likelihood estimation. Model convergence was ensured by increasing the maximum number of iterations and using adaptive control settings (clmm.control). All predictors were included as fixed effects, except for genus, which was included as a random intercept to account for the nonindependence of species within taxonomic groups and was specified in the model as (1 | genus). This structure allowed us to untangle species-specific effects from taxonomic clustering, while quantifying variation explained by taxonomy. As only 1.2% of assessments involved a two-step transition ($n = 61$), we modeled extinction risk change as a three-category ordered response (improvement, stability, and deterioration) rather than as a numerical scale because it would provide no additional analytical information under these conditions. In our CLMM, two threshold parameters were estimated dividing the latent probability of extinction risk change into these three categories. The weight (β) of predictors in the CLMM was quantified on the log-odds scale and exponentiated to obtain cumulative odds ratios [$\exp(\beta)$], representing the multiplicative change in the odds of falling in a higher- versus lower-risk response category per unit change in the predictor, with categories ordered as improvement < stability < deterioration in status. Under the proportional odds assumption of the CLMM, this odds ratio was constant across the two cumulative thresholds of the response. To quantify the proportion of variance explained by

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TABLE 1 Predictors of change in extinction risk divided into four broad classes, with the type of variable and the number of levels (for factors and ordinal variables) or range of values (for numeric variables) reported for each (full description of categorical levels and reference categories is provided in Appendix S1).

Class	Predictor	Type
Exposure to extrinsic pressure	Initial category of risk[a]	Ordinal (eight levels)
	Number of threats[b]	Numeric (1–11)
	Ecological systems[c]	Factor (three levels)
	Number of habitat typesd	Numeric (1–14)
	Biogeographic realms[d]	Factor (seven levels)
Intrinsic vulnerability	Taxonomic order	Factor (14)
	Taxonomic genus	Random factor (1,191)
	Adult body mass[e]	Numeric (1.6 to 1.49×10^8 g)
	Litter size[f]	Numeric (0.9–16.89)
	Trophic level[g]	Factor (three levels)
	Diet breadth[h]	Numeric (1–5)
	Activity cycle[i]	Factor (three levels)[1]
Conservation actions	Number of conservation actions[b]	Numeric (1–11)
Temporal covariate	Time since baseline[j]	Numeric (19–30 years)

[a]Initial category of risk: International Union for Conservation of Nature (IUCN) Red List category assigned to each species. Extinct in the wild (EW) and critically endangered (possibly extinct) (CR[PE]) collapsed into extinct (EX).
[b]Number of threats, habitats, and conservation actions: total counts recorded for each species in Red List assessment.
[c]Ecological system: broad classification of the primary ecological system occupied by each species. Species associated with multiple systems were assigned to a single system based on their primary ecological association.
[d]Biogeographic realms: assignment of each species to one of eight biogeographic regions following the WWF classification (Olson et al., 2001). The Australasian realm was merged with Oceania and Antarctic. Species occurring across three or more realms were assigned to a many realm category.
[e]Adult body mass: species mean body mass in grams.
[f]Litter size: mean number of offspring per reproductive event.
[g]Trophic level: classification of each species based on primary food source.
[h]Diet breadth: number of prevalent dietary categories (≥20% of diet) consumed, derived from EltonTraits (Wilman et al., 2014).
[i]Activity cycle: temporal activity pattern of each species.
[j]Time since baseline: number of years elapsed between 1996 and the most recent assessment for each species.

the model, we calculated marginal and conditional R^2 following the methods of Nakagawa and Schielzeth (2013) and Nakagawa et al. (2017). The marginal R^2 reflects the variance explained by the fixed effects, whereas the conditional R^2 incorporates both fixed and random effects, providing an estimate of the total variance accounted for by the model. These indices were calculated using the performance package in R, which implements the standard variance-partitioning approach for mixed-effects models with ordinal responses.

We modeled change in extinction risk as a function of 14 predictors (Table 1). When one or more values were missing from the COMBINE dataset (343 species), we imputed them based on values from congenerics (mode for categorical and median for numeric variables).

Species already classified as EX in 1996 were excluded from the analysis, as they could not be assigned a meaningful direction of change. All other species were retained, including those that transitioned to EX during the study period. For tracking changes in extinction risk, we followed the Red List Index methodology (Butchart et al., 2007), merging critically endangered possibly extinct (CR[PE]) and EW with EX into a single terminal category, for a total of 4,992 species. We included time since baseline (i.e., years elapsed between 1996 and the most recent assessment) as a temporal covariate to account for the uneven temporal distribution of reassessments across taxa. Species belonging to multiple ecological systems (i.e., terrestrial, freshwater, and marine) were reassigned to a single, predominant system (Appendix S2). We merged the Antarctic and Oceania regions with Australasia because they contained few species. Taxa associated with more than one biogeographic realm were assigned to a separate level (i.e., multirealm). Orders comprising more than 30 species were retained as separate levels. Cetaceans (order Artiodactyla) and pinnipeds (order Carnivora) were extracted from their respective orders and merged with sirenians (order Sirenia) to form a distinct group (i.e., marine mammals). To prevent very small sample sizes, all orders with fewer than 30 species were grouped according to body size, a trait known to be strongly associated with extinction risk and widely used to classify mammalian species in macroecological studies (Cardillo et al., 2005; Ripple et al., 2017). The other small mammals group clustered Microbiotheria, Macroscelidea, Scandentia, Peramelemorphia, Hyracoidea, Tubulidentata, Notoryctemorphia, and Paucituberculata, whereas the other mammals group referred to Perissodactyla, Dermoptera, Monotremata, Cingulata, Pilosa, Pholidota, and Proboscidea. We log-transformed adult mass and litter size to reduce skewness in their distributions and improve interpretability, and other continuous variables were standardized (mean = 0, SD = 1) to aid model fitting and comparability of coefficients. For categorical predictors, we

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TABLE 2 Comparison of International Union for Conservation of Nature (IUCN) Red List categories for mammals between 1996 and the most recent available assessment (2015–2025), where values represent the number (no.) of species in each Red List category at each time point.

Category[a]	Net change[b]	No. in 1996	% in 1996	No. in 2015–2025	% in 2015–2025
EX	+3	85	1.67	88	1.73
EW	−1	2	0.04	1	0.02
CR(PE)	+8	14	0.28	22	0.43
CR	+53	153	3.01	206	4.06
EN	+34	493	9.71	527	10.4
VU	+64	471	9.28	535	10.54
NT	−5	385	7.60	380	7.48
LC	−156	3474	68.43	3318	65.36
Total		5077		5077	
Threatened[c]		1133	22.70	1291	25.43

[a]EX, extinct; EW, extinct in the wild; CR(PE), critically endangered (possibly extinct); CR, critically endangered; EN, endangered; VU, vulnerable; NT, near threatened; LC, least concern.
[b]Changes between periods reflect net changes in category occupancy (i.e., the balance between species entering and leaving each category: positive values indicate a net increase in the number of species in that category, and negative values a net decrease). These net changes do not correspond to the proportion of species that underwent genuine deterioration, as intermediate categories may simultaneously gain and lose species.
[c]Threatened = [(VU + EN + CR + CR(PE) + EW) / (Total − EX)] × 100.

set reference levels based on the categories with the largest number of species to facilitate interpretation of model coefficients. The reference level was set to LC for threat, omnivore for trophic level, nocturnal for activity cycle, terrestrial for ecological systems, Neotropical for realms, and Rodentia for orders.

To ensure the robustness of our findings, we performed three sensitivity analyses (Appendices S2 & S3): an analysis restricted to species with no imputed trait values ($n = 4{,}746$) to test whether trait imputation influenced our results; an analysis restricted to single-step transitions only ($n = 4{,}911$), controlling for the structural asymmetry of the Red List categories; and a phylogenetic sensitivity analysis including the first eight principal coordinate axes derived from a majority-rule consensus tree of the Upham et al. (2019) mammal phylogeny ($n = 4{,}467$) to account for phylogenetic nonindependence beyond the genus-level random effect.

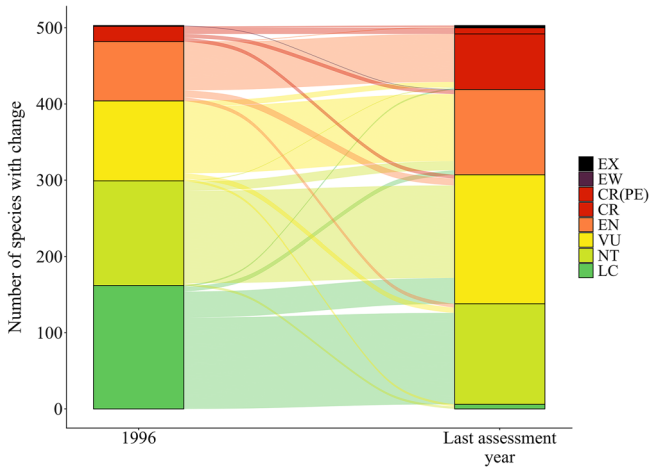


FIGURE 1 Species transitioning from 1996 to the most recent International Union for Conservation of Nature (IUCN) assessment categories (2015–2025). Only species that underwent a genuine category change are shown ($n = 503$). Flow width is proportional to the number of species moving between categories. Colors follow the official IUCN Red List color palette. EX, extinct; EW, extinct in the wild; CR(PE), critically endangered (possibly extinct); CR, critically endangered; EN, endangered; VU, vulnerable; NT, near threatened; and LC, least concern.

RESULTS

Of the 5,077 data-sufficient species last assessed after 2014, threatened species (VU + EN + CR, including CR[PE] and EW) represented 26% of extant assessed species (i.e., excluding EX from the denominator; Table 2, revised from Hoffmann et al., 2011). For the analysis of correlates of change, we excluded species already classified as EX in 1996, yielding 4,992 species. Of these, 3,318 species were LC; 380 were NT; 535 were VU; 527 were EN; 206 were CR; 22 were CR(PE); one was EW; and three were EX. By comparing corrected 1996 categories with the most recent assessment for these species, 4,489 remained stable (90%); 465 deteriorated in status (9.3%); and 38 improved in status (0.8%) (Figure 1).

The CLMM explained a substantial proportion of the variation in extinction risk trajectories. The R^2 indicated that fixed effects (i.e., initial category of risk, number of threats, ecological systems, number of habitat types, realms, orders, adult body mass, litter size, trophic level, diet breadth, activity cycle, number of conservation actions, and time since baseline) accounted for approximately 32% of the variance, whereas including genus as a random effect increased the R^2 to 47%.

Our sensitivity analyses confirmed that the model was robust to trait imputation, the structural asymmetry of the Red List categories, and phylogenetic nonindependence; the direction, magnitude, and significance of all key predictors were consistent across the main model and all sensitivity analyses (Appendix

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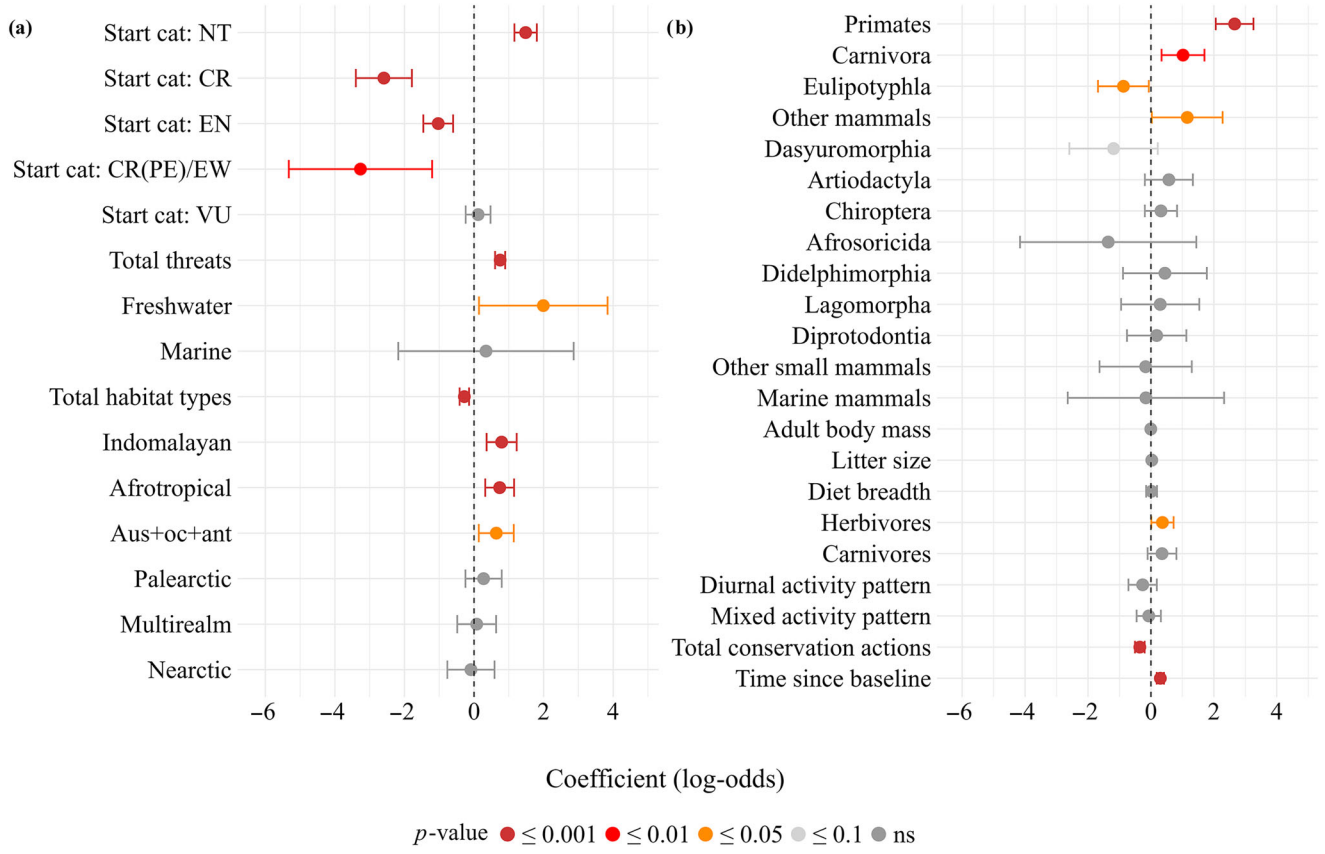


FIGURE 2 Estimated effects of fixed predictors on changes of mammal extinction risk from a cumulative link mixed model (CLMM). Panel (a) shows predictors related to the class of exposure to extrinsic pressures, whereas panel (b) shows the classes of intrinsic vulnerability, conservation actions, and temporal covariate (see Table 1 for full predictor descriptions). Points indicate coefficients, with 95% confidence intervals. Color indicates significance level, ranging from dark red ($p \leq 0.001$) to dark grey (nonsignificant). Positive values indicate higher probabilities of moving toward a deterioration in status along the improvement–stability–deterioration gradient, whereas negative values indicate lower probabilities. Reference levels are LC (initial category of risk), neotropical (biogeographic realm), terrestrial (ecological system), omnivores (trophic level), nocturnal (activity cycle), and Rodentia (taxonomic order).

S3). We therefore focused on these robust predictors, which we considered the most reliable correlates of extinction risk dynamics.

NT species had over four times higher odds of a deterioration in status rather than stability or an improvement compared with those listed as LC (log-odds = 1.48, $z = 9.03$, $p \leq 0.001$), whereas species starting from EN (log-odds = −1.03, $z = -4.72$, $p \leq 0.001$) or CR (log-odds = −2.59, $z = -6.31$, $p \leq 0.001$) were more likely to remain stable or improve (i.e., move to a lower-risk category [approximately three or 13 times lower odds, respectively]) (Figure 2; Appendix S3). This elevated deterioration for NT species persisted when restricting the analysis to single-step transitions, confirming that it was not solely explained by their greater number of available higher-risk Red List categories (Appendix S3).

Species facing more threats were more likely to experience an increase in their extinction risk (log-odds = 0.75, $z = 10.10$, $p \leq 0.001$). The odds of a deterioration in conservation status decreased with the number of habitat types occupied (log-odds = −0.28, $z = -4.01$, $p \leq 0.001$). Species from the Indomalayan (log-odds = 0.79, $z = 3.48$, $p \leq 0.001$), Afrotropical (log-odds = 0.74, $z = 3.59$, $p \leq 0.001$), and Australasian, Oceanian, and Antarctic (log-odds = 0.64, $z = 2.50$, $p = 0.013$) realms had approximately two times higher odds of experiencing a deterioration in status than those from the reference realm (Figure 2; Appendix S3).

Compared with Rodentia (reference group), Primates showed the strongest tendency to deteriorate in status (approximately 14 times higher odds; log-odds = 2.66, $z = 8.69$, $p < 0.001$) (Figure 2; Appendix S3). Conservation actions were associated with lower odds of a deterioration in status (log-odds = −0.35, $z = -4.50$, $p \leq 0.001$). Finally, species with a longer assessment interval showed higher odds of deteriorating in conservation status across the observed range of 19–30 years (log-odds = 0.30, $z = 5.07$, $p \leq 0.001$).

Marginal predictions illustrated the associations between threats, habitat types, conservation actions, time since baseline, and extinction risk trajectories (Figure 3). The probability of a deterioration in status increased steeply with the number of threats, reaching approximately 40% when more than 10 threats co-occurred, whereas the probability of moving toward a lower-risk category remained near zero (Figure 3a). Conversely, the probability of deterioration decreased with the number of habitat types, approaching one beyond approximately 10 habitats

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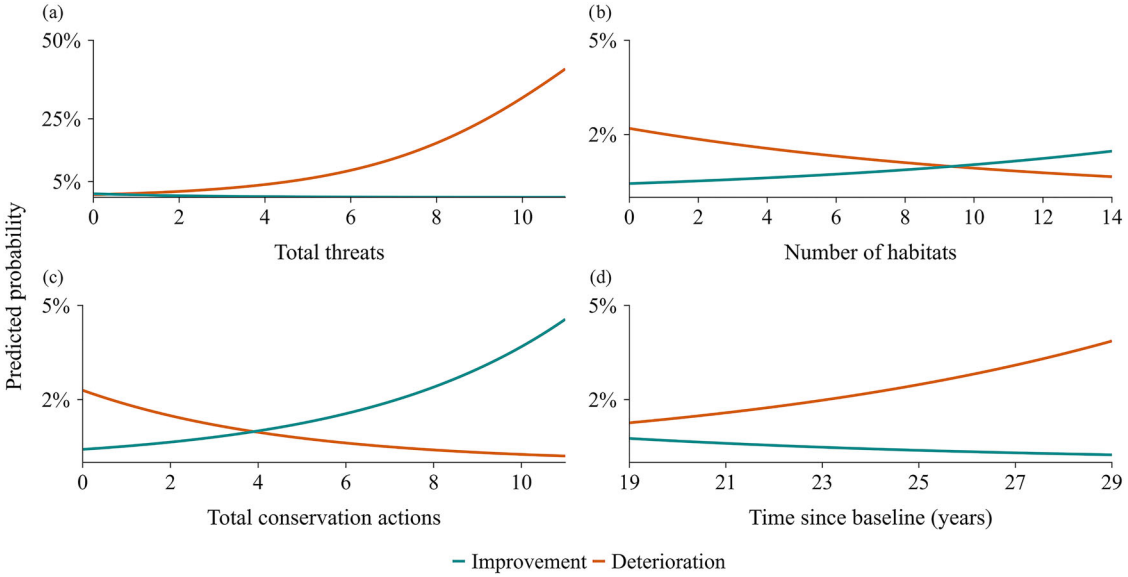


FIGURE 3 Probability of extinction risk of 4,992 data-sufficient species of mammal deteriorating (orange) or improving (green), as a function of the number of threats (a), habitat types (b), conservation actions (c), and time since baseline (d) per species, derived from the cumulative link mixed model.

and was accompanied by an increase to approximately 2% in the probability of improvement in status at more than 12 habitats (Figure 3b). As the number of conservation actions increases, the probability of improvement increased, approaching 5% in species receiving more than 10 actions, whereas the probability of deterioration decreased to zero (Figure 3c). Finally, the probability of deterioration increased with the time elapsed since the baseline assessment. Across the observed range of reassessment intervals (19–29 years), the likelihood of experiencing a deterioration in status increased from approximately 2% to 4%, mirrored by a corresponding decline in the probability of improvement in status (Figure 3d).

DISCUSSION

Our analysis showed that overall, the conservation status of most mammal species remained stable over time. Approximately 9% of mammal species moved to a higher extinction risk category, whereas genuine improvements in status remained very rare, occurring in less than 1% of cases. Hoffmann et al. (2011) recorded 171 genuine deteriorations and 24 improvements in status between 1996 and 2008. Deteriorations in conservation status were mainly associated with exposure to extrinsic pressures (see Table 1), particularly the initial Red List category (i.e., 1996 category), the number of threats to which species were exposed, and the biogeographic context. Primates, NT species, species facing multiple threats, and those from the Indomalayan region exhibited the highest probability of a deterioration in status. In contrast, improvements in status were associated with broader habitat use and the implementation of conservation actions. CR species were least likely to further deteriorate in status, a pattern consistent with the concentration of targeted conservation efforts for such species (Bolam et al., 2021), whereas species occupying more habitat types had the lowest risk of further deterioration in status. Species benefitting from many conservation actions exhibited a marginally reduced probability of deterioration in conservation status.

Our findings highlighted the distinct extinction risk dynamics of NT species, which showed the highest probability of deterioration relative to all other starting categories. According to the IUCN criteria, NT species fail to qualify as threatened, although their population size or habitat loss is close to the threshold for VU species (IUCN Standards and Petitions Committee, 2024; Mace et al., 2008). This scenario implies that many NT species are already undergoing substantial reductions—either in population size or in other metrics used for Red List assessment (e.g., range size under Criterion B)—before a change in status is triggered (Butchart et al., 2007). Moreover, the step between NT and VU is relatively narrow compared with transitions between higher threat categories (e.g., VU to EN), meaning that moderate declines (typically around 20–30% over three generations) may be sufficient to move a species from NT into VU (IUCN, 2012; Mace et al., 2008). In contrast, threatened species, such as EN and CR species, typically receive more targeted conservation efforts, which may help improve or at least stabilize their conservation status and reduce the possibility of further deterioration (Bolam et al., 2021; Hoffmann et al., 2010; Lacher et al., 2025). This asymmetry suggests that conservation actions tend to be implemented only after declines have become severe, leaving NT species (and presumably also many slowly declining LC species) particularly at risk during the initial, and often steepest, phase of population decline (Wilson et al., 2011), when absolute reductions translate into proportionally larger decreases (Mace et al., 2008). Several lemur species of the genus *Avahi*, for instance, were classified as LC in 1996 despite ongoing and well-documented deforestation across Madagascar. All have since deteriorated to VU, exemplifying how species can pass through

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the early phase of decline undetected and without triggering a conservation response. Similarly, the okapi (*Okapia johnstoni*) was NT in 1996 despite well-documented threats from illegal hunting and habitat loss in the Democratic Republic of Congo, and it has since deteriorated to EN, a trajectory that earlier investment in antipoaching enforcement and community-based conservation might have altered.

Overall, the number of different types of threats influenced the probability of deterioration in conservation status significantly but with less strength than other predictors. Although Greenville et al. (2021), in a large-scale analysis of >10,000 vertebrate species, found that a higher number of threats does not consistently translate into higher risk of decline, our analysis revealed a clear logistic relationship between the number of threats and the probability of deterioration in status for mammals: species exposed to 10 or more threats showed markedly elevated probabilities of extinction risk. Although threat attribution in the Red List can be inconsistent across assessors and assessment cycles, reflecting variation in assessor expertise and data availability rather than true threat intensity (Humphries et al., 2026), the logistic relationship we observed between the number of threats and the probability of deterioration in status was consistent with the results of earlier studies demonstrating that multiple small threats can drive extinction risk over time and that interactions among threats may escalate risk beyond what would be expected from their individual contributions (Kimmel et al., 2022). Similarly, species-specific analyses indicate that vulnerability to different threats can vary depending on the type of pressure and biological traits, with some species showing strong declines when exposed to combinations of threats (Isaac & Cowlishaw, 2004).

Patterns of change in extinction risk varied markedly across biogeographic realms and taxonomic orders. These patterns may reflect well-documented threats for each group, although our model focused on the total number of threats rather than directly testing the contribution of specific sources. The Indomalayan realm emerged as the region with the highest probability of species experiencing a deterioration in status, which is consistent with similar findings from previous analyses (Hoffmann et al., 2010). The broader conservation literature reports intense pressures in this region including deforestation, land-use change, and overexploitation of wildlife on both land and sea (Braulik et al., 2023; Chen et al., 2024; Maxwell et al., 2016; Vijay et al., 2016; Wilcove & Koh, 2010). The Afrotropical realm also exhibited a high risk of species experiencing a deterioration in status, alongside established evidence of illegal hunting and bushmeat exploitation disproportionately affecting large mammals in African countries (Ripple et al., 2016; Schipper et al., 2008). In our analysis, we merged the Australasian realm with the Oceania realm, which shares closely related faunal assemblages (Cox, 2001; Morrone, 2015), and with the Antarctic realm, whose extremely low mammal diversity (i.e., only two realm-specific mammals, *Arctocephalus gazella* and *Ommatophoca rossii*) limits its relevance for comparative analysis. Overall, this cluster ranked third in terms of deterioration in status risk, which may reflect the pervasive impact of invasive species on island faunas across Australia, New Zealand, and the Pacific Islands (Doherty et al., 2016; Hoffmann et al., 2011; Woinarski et al., 2015).

Primates exhibited an elevated risk of deterioration in conservation status relative to other groups. Of the 508 primate species included in our dataset, 346 are currently threatened (VU to EW), and of these, 261 are concentrated in the three realms showing the highest deterioration risk in our analysis—Indomalayan, Afrotropical, and Australasian regions. Moreover, 149 primate species underwent a genuine category change during the study period, with seven, 29, and 72 species deteriorating in status in the Australasian, Indomalayan, and Afrotropical realms, respectively. Intense and converging pressures have been described for this group, particularly in tropical regions where human population density and land-use change are rapidly increasing (Estrada et al., 2017) and overexploitation remains a major concern (Badihi et al., 2024; Garber et al., 2024; Mancini et al., 2023). Their established slow life histories, small and fragmented ranges, and high degree of dietary and social specialization may further exacerbate primate vulnerability to environmental change (Estrada et al., 2017; Garber et al., 2024).

Analysis of phylogenetic structure revealed that change in extinction risk was strongly clustered within genera. Model performance suggested that closely related species are exposed to similar threats and share hidden vulnerabilities (Fritz & Purvis, 2010; Verde Arregoitia, 2016). To verify that our results were not driven by broad phylogenetic trends in the data, we included phylogenetic principal coordinate axes as additional predictors; the main associations remained unchanged, confirming that the identified correlates of extinction risk dynamics are robust to the inclusion of phylogenetic structure. However, such patterns should be interpreted with caution, because fine-scale taxonomic structure can also capture idiosyncratic variation—for example, when a single species within a genus experiences a unique threat or conservation intervention that does not apply to its close relatives (Freckleton, 2009). Moreover, the phylogenetic analysis was restricted to the subset of species with available phylogenetic data (89.6%), which may limit the generalizability of these phylogenetic comparisons.

Generalist species had a higher probability of remaining stable or improving their conservation status. Our model indicated that species occupying many habitat types were less likely to deteriorate in conservation status, consistent with the idea that generalists are less sensitive to environmental shifts than specialists (Gaston & Blackburn, 2000; Purvis et al., 2000). We found no significant association between biological traits such as body mass, litter size, diet breadth, and activity cycles and the probability of change in extinction risk. One possible explanation for this result was that the increasing intensity of human pressures overshadows species-level biological tendencies, leaving little variation in extinction trajectories to be explained by intrinsic traits alone (Di Marco et al., 2018). This scenario suggests that traits that correlate with extinction risk do not necessarily function as correlates of change in extinction risk. Although intrinsic traits can help explain why some species are more threatened than others at a given time, the deterioration in a species' conservation status is more strongly driven by extrinsic pressures, which tend to override trait-based differences in

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species' risk responses (Di Marco et al., 2018; Maxwell et al., 2016). As a result, intrinsic traits may have limited predictive power when the focus shifts from explaining which species are threatened at a given time to explaining which species are becoming more threatened over time. Nevertheless, as Red List category changes are a coarse metric, they may be insufficient to detect subtle trait-mediated effects, and biological differences among species may influence extinction risk trajectories at finer scales than those captured by IUCN categories. Functional traits may prove more informative at finer scales of analysis, where the resolution of the response variable is sufficient to detect their influence (Di Marco et al., 2018).

The total number of conservation actions emerged as a significant predictor of improvement in status, although it was a weaker predictor than the number of threats. Although associated with improvements in conservation status, conservation interventions are often spatially restricted or not sufficiently incentivized to halt broader extinction trends (Hoffmann et al., 2010; Langhammer et al., 2024). The few improvements that occurred overall underscore the urgency of addressing multiple threats simultaneously and ensuring that change is monitored and actions are repeated or adapted if and as necessary (Kimmel et al., 2022). The Iberian lynx (*Lynx pardinus*), for instance, moved from CR in 1996 to VU following decades of captive breeding, reintroduction, prey base restoration, and habitat management, illustrating how multi-action, sustained interventions can support genuine recovery. This association should be interpreted cautiously: species receiving more conservation attention may simply have more actions listed (Bolam et al., 2021), and coded actions often reflect recommendations rather than implemented interventions, with coding practices varying across taxa and assessors. Such inconsistencies can introduce assessor bias and potentially distort the relationship between coded conservation actions and observed improvements.

Beyond this consideration, several additional limitations exist. First, the breadth of the Red List categories, together with the life-history characteristics and long generation times of many of the species being considered, means that substantial changes (i.e., both declines and increases) can occur within an extinction risk category before a species moves to the next level of threat. Additionally, the boundary between genuine and non-genuine change is not always clear-cut. Some changes classified as genuine, even after backcasting, may partly reflect data availability rather than true biological deterioration. Backcasting relies on standardized criteria but involves expert judgment, and its outcomes may vary depending on the assessors involved, introducing a degree of subjectivity. Future approaches could use population trend data, available for a subset of species in the IUCN Red List, as an independent validation of genuine change, allowing a cross-check between modeled category and observed demographic trajectories. Another limitation concerns the quality and structure of threat and conservation action data in the Red List. Threat attribution can be heterogeneous and only partially supported by species-specific empirical evidence, with recent analyses showing that a relatively small proportion of threat assignments are based on quantitative data (Humphries et al., 2026). This introduces uncertainty when using the number of threats as a predictor of changes in extinction risk. Moreover, our model tested only the total number of threats rather than their specific sources, and the mechanisms underlying the observed patterns should therefore be interpreted considering the broader literature rather than as direct model outputs. This scenario highlights the need for more systematic and standardized coding of the correlates of deterioration and of the key actions underpinning improvements within the Red List process. Finally, another source of uncertainty relates to the many species listed as LC, which receive limited attention compared with threatened species, resulting in possible undetected changes in extinction risk. Notably, 441 LC species in our dataset currently have a decreasing population trend, indicating ongoing declines that may eventually push them above the thresholds for NT or threatened categories. Because LC species are often widespread ecological generalists, this may also help explain why species occupying many habitat types showed a lower probability of deterioration in status, as broad habitat use frequently coincides with wide distribution and lower baseline extinction risk. Moreover, scientific attention and funding tend to be biased toward species of commercial, recreational, or charismatic value (Guy et al., 2021), regardless of their conservation status—potentially leaving many declining LC and NT species, which lack such appeal, underrepresented in the literature and underprotected in practice.

Overall, mammal populations are continuing to decline, with the number of threats a species faces emerging as a strong predictor of a deterioration in conservation status. Despite decades of conservation effort, resulting in limited improvements in conservation status for a few species, many species continue to edge (or in some cases rush) toward higher extinction risk. Understanding which species are subject to a deteriorating conservation status and where and why is essential for guiding timely and effective conservation action (Hoffmann et al., 2010; IPBES, 2019). Our findings highlight a critical window of opportunity: acting early, particularly for NT species, can prevent the potentially irreversible slide into higher threat categories. Evidence from successful conservation planning initiatives (e.g., IUCN SSC Conservation Planning Specialist Group [CPSG]-led programs) demonstrates that well-designed, proactive interventions can halt or reverse declines when implemented before populations have reached critical thresholds (Lees et al., 2021; Reuter et al., 2022). Our study therefore underscores the urgency of matching reactive interventions for highly threatened species with proactive conservation for those at lower risk, prioritizing early intervention, and sustaining long-term, threat-targeted actions to safeguard global mammal biodiversity.

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DATA AVAILABILITY STATEMENT

The R code and the derived dataset used in all analyses are permanently archived on Zenodo (https://doi.org/10.5281/zenodo.22102019) under a Creative Commons Attribution 4.0 International (CC BY 4.0) license.

ORCID

Claudia Fornarini https://orcid.org/0009-0006-8863-0112
Craig Hilton-Taylor https://orcid.org/0000-0003-1163-1425
Mike Hoffmann https://orcid.org/0000-0003-4785-2254
Rosalind J. Kennerley https://orcid.org/0000-0002-3869-5843
David L. Waldien https://orcid.org/0000-0002-5319-5396
Gill T. Braulik https://orcid.org/0000-0001-8919-4187
Leandro Jerusalinsky https://orcid.org/0000-0003-0744-1987
Gianna Minton https://orcid.org/0000-0003-4284-2540
Randall R. Reeves https://orcid.org/0000-0002-6512-6507
Elizabeth A. Williamson https://orcid.org/0000-0001-6848-9154
Carlo Rondinini https://orcid.org/0000-0002-6617-018X

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