Forest quality mitigates extinction risk in humid tropical vertebrates

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Abstract

Reducing deforestation underpins efforts to conserve global biodiversity. However, this focus on retaining forest cover[1–4] overlooks the multitude of anthropogenic pressures that can degrade forest quality in ways that may imperil biodiversity[5]. Here we use the latest remotely-sensed measures of forest structural condition and associated human pressures across the global humid tropics[6,7] to provide the first estimates of the importance of forest quality, relative to forest cover, in mitigating extinction risk for rainforest vertebrates worldwide. We found tropical rainforests of intact structural condition and minimal human pressures played an outsized role in reducing the odds of species being threatened or having a declining population. Further, the effects of forest quality in mitigating extinction risk were stronger when small amounts of high quality forest remained within species geographic ranges, as opposed to when large extents were forested but of low quality. Our research underscores a critical need to focus global environmental policy and conservation strategies toward the targeted protection of the last remaining undisturbed forest landscapes, in concert with strategies aimed at preserving, restoring and reconnecting remnant forest fragments across the hyperdiverse humid tropics.

Main

Conservation efforts to date have largely failed to arrest the global biodiversity crisis[8,9]. The ongoing loss of biodiversity imperils the myriad ecosystem functions and services that people receive from nature[10,11]. Consequently, halting biodiversity loss is imperative to sustained human wellbeing[9–11]. Emerging evidence suggests undisturbed native forests with negligible human pressures support greater biodiversity and ecosystem service values than lands converted and degraded for agriculture and forestry[12–14]. However, international environmental agreements such as the Convention on Biological Diversity (CBD)[1], the New York Declaration on Forests[2], the 2030 Agenda for Sustainable Development[3] and the United Nations Framework Convention on Climate Change[4] typically mandate the maintenance and restoration of forest cover, without prescribing clear targets to achieve the preservation of native forest quality.

Tropical rainforests, the most biodiverse terrestrial ecosystems on Earth[15], are currently undergoing an accelerated rate of conversion and degradation[16–18]. Less than half of the global tropical rainforest estate remains in its native state characterized by tall, closed-canopy stands free from deleterious human activities[6,7]. The steady degradation and loss of these 'best of the last' remaining rainforests foreshadows a disproportionately high rate of imminent extinctions, given their hyperdiversity[7,15,19]. Yet, there is a lack of direct evidence on whether native tropical rainforests of intact structural condition and minimal human pressures are associated with reduced species extinction risk. Such evidence on the potential for undisturbed native rainforests to mitigate species extinction risk is critical for supporting the inclusion of forest quality targets in upcoming international environmental agreements such as the CBD's post-2020 Global Biodiversity Framework[20].

Advances in remote sensing have recently facilitated the development of two fine-scale, pantropical measures of rainforest quality[6], which for the first time provide the capability to quantify the importance of the last remaining native tropical rainforests of intact structural condition and low human pressures in mitigating species extinction risk. The Structural Condition Index (SCI), a globally consistent measure of forest structure, enables identification of taller, older, more structurally complex, closed-canopy rainforests (hereafter "structurally intact forests")[6]. Structurally intact forests may deteriorate in quality with anthropogenic pressures such as settlements, roads, fire, selective logging and hunting, and the adverse impacts of such pressures on biodiversity may surpass those of deforestation alone[5]. To capture such pressures, the Forest Structural Integrity Index (FSII)[6] combines the SCI with the Human Footprint (HFP)[21] to distinguish rainforests of intact structural condition *and* minimal human modification (hereafter "high integrity forests").

Here, we present the first assessment of the global importance of native high integrity forests in mitigating species extinction risk, compared with structurally intact forests and forest cover alone (*i.e.,* without consideration of either structural condition or integrity). We use two IUCN Red List of Threatened Species[22] measures of extinction risk: (1) threatened status and (2) declining population for 16,396 mammal, bird, reptile, and amphibian species whose geographic ranges overlap the tropical rainforest biome[23]. We classified species as either rainforest endemic or non-endemic on the basis of extent of range overlap with the tropical rainforest biome and association with rainforest habitats[15], expecting the potential effects of forest quality in mitigating extinction risk would be stronger for endemic or rainforest dependent species than for non-endemics. Within species ranges, we used the SCI and FSII datasets to calculate the area (km^2) of structurally intact and high integrity forests, relative to the area of structurally degraded and low integrity forests. We also pooled all SCI values representing forest to calculate the total area of forest cover within species ranges, relative to non-forest area. We then used a generalized linear modeling framework that accounts for the phylogenetic non-independence of species[24] to test whether greater area of high integrity forests within species ranges is linked to a reduced odds of species: (i) being threatened, and (ii) having a declining population, relative to greater area of structurally intact forests and forest cover alone. Further, we test whether the potential effects of forest quality in reducing the probability of species extinction risk are stronger when small amounts of high quality forest remain within species ranges, as opposed to when large extents are forested but of low quality.

Across all endemic as well as non-endemic vertebrate groups, high integrity forests were associated with significantly lower odds of extinction risk compared with forest cover alone (Fig. 1; 95% confidence intervals of estimated standardized coefficients did not overlap zero and false discovery rate (FDR)-adjusted $p < 0.05$, Supplementary Table 2). For example, among endemic mammals with average area of structurally intact forest and forest cover within their ranges, the odds of being threatened reduced by 59.7% (95% CI: 51.8 – 67.0) for each 1% increase in high integrity forest area. In contrast, among endemic mammals with average area of structurally intact and high integrity forest within their ranges, each 1% increase in forest cover area was associated with a 32.3% (0.0 – 76.8) *increase* in the odds of being threatened (Fig. 1: closed circles). This greater likelihood of extinction risk with increasing forest cover may be surprising given forest cover is known to have a positive effect on biodiversity[19]. However, the odds reported here are derived from standardized partial regression coefficients representing unbiased estimates of the effects of forest cover alone on species extinction risk, relative to structurally intact and high integrity forests (*i.e.,* controlling for the effects of the forest quality variables by statistically holding them at their average values)[25,26]. Therefore, our results reflect how structural degradation and human pressures within forest cover alone can be detrimental to biodiversity, when isolated from and directly compared with high integrity forests.

We observed a general tendency for structurally intact forests to be associated with lower odds of species extinction risk than forest cover alone. This pattern was stronger in some groups (*e.g.,* endemic and non-endemic birds being threatened and amphibians having a declining population, Fig. 1) than others (*e.g.,* non-endemic reptiles having a declining population). However, structurally intact forests tended to be associated with higher odds of species extinction risk than high integrity forests, with this pattern again being stronger in some groups (*e.g.,* endemic and non-endemic mammals, reptiles and amphibians being threatened, Fig. 1) than others (*e.g.,* endemic birds having a declining population). Inconsistent with our expectations, the strength of the effects of high integrity forests in mitigating extinction risk was largely similar for endemic and non-endemic vertebrates (95% CIs overlapped each other, Fig. 1).

We found robust support for high integrity forest fragments playing a more important role in mitigating species extinction risk than larger forested extents of low integrity. Endemic as well as non-endemic vertebrates had a lower probability of being threatened and having a declining population when small amounts of high integrity forest remained within species humid tropical ranges, as opposed to when large extents were forested but of low integrity (Fig. 2). Evidence for this finding is the strong positive statistical interaction (95% CIs did not overlap zero and FDR-adjusted $p < 0.05$) between forest cover and integrity in 10 out of 16 models testing for such interactions on both response variables for each taxonomic group. A further four interactions tended to be positive albeit statistically non-significant (95% CIs overlapped zero and FDR-adjusted $p > 0.05$; Supplementary Table 3). Across all endemic and non-endemic vertebrate groups, we also found species had a lower probability of being threatened and having declining populations when small amounts of high integrity forest remained within species humid tropical ranges, compared with when larger extents remained structurally intact but of low integrity (Fig. 3). Support for this finding lies in the strong positive statistical interaction between forest condition and integrity in nine out of 16 models testing for such interactions on both response variables for each taxonomic group. A further six interactions tended to be positive albeit statistically non-significant (Supplementary Table 4). These patterns were consistent for the interactions between forest cover and condition on both response variables (Extended Data Fig. 1, Supplementary Table 5). However, inconsistent with these widespread trends, endemic birds, reptiles and amphibians had a lower probability of having declining populations only when large extents of high quality forest remained within species ranges (Figs. 2-3, Extended Data Fig. 1), as supported by the negative interactions between forest cover, integrity and condition on declining population probability in six out of 48 models (Supplementary Tables 3-5).

Reducing deforestation is a central pillar of global biodiversity conservation efforts[1–4]. Yet, this attention on maintaining forest cover alone ignores the many human pressures that can degrade the quality of forest cover in ways severely detrimental to biodiversity. Leveraging the latest advances in remote sensing, we provide the first estimates of the importance of forest quality, relative to forest cover, in mitigating extinction risk for humid tropical vertebrates worldwide. Our analyses reveal the last remaining high integrity forests play a significant role in reducing species extinction risk for all vertebrate groups, and serve as critical habitats not only for species that occur exclusively in these ecosystems, but also for species that use them as refugia or on a seasonal basis (*e.g.,* wintering migratory birds[15]). Forest cover is known to have a positive effect on biodiversity, relative to human land-uses such as agriculture and development[19]. However, when compared with high integrity forests for the first time in this study, forest cover was linked to a higher likelihood of species extinction risk, reflecting how structural degradation and human pressures within forest cover alone can adversely affect biodiversity. Furthermore, structurally intact forests tended to be associated with higher odds of species extinction risk than high integrity forests, suggesting structural intactness alone can be insufficient to prevent biodiversity loss without also limiting human pressures within intact forests.

Large, well connected forest landscapes are known to be essential for biodiversity conservation, especially in an era of climate change[13,14,19]. However, our research shows the effects of forest quality in mitigating extinction risk for humid tropical vertebrates were amplified when small amounts of high integrity forest remained within species ranges, compared with when large extents were forested or remained structurally intact but were of low integrity. Our findings add to the growing evidence that high integrity forest fragments can play a vital supporting role in limiting biodiversity loss by providing refugia or habitat for numerous species, and are thus worthy of inclusion in conservation planning[7,27,28]. Nevertheless, small forest fragments face a higher likelihood of loss than larger forested tracts because of the severe land-use pressures around them and improved access for resource extraction[29]. Furthermore, sensitivity to isolation in forest fragments may likely explain the higher probability of declining populations even in high integrity forest fragments for endemic birds, reptiles and amphibians[30], potentially signaling the presence of an extinction debt for these vertebrate groups in fragmented landscapes[19]. Therefore, proactively prioritising the protection of high integrity forest fragments from loss, while simultaneously setting targets for restoring degraded forest fragments and re-establishing landscape connectivity is of paramount importance for limiting biodiversity loss[27].

The positive role of high integrity forests in mitigating species extinction risk remained evident even after excluding threatened vertebrates under criterion B of the IUCN Red List[22] (Extended Data Fig. 2, Supplementary Tables 6-7). Species assessed under criterion B have restricted geographic ranges, the habitats within which may be severely fragmented[22]. The exclusion of criterion B species avoids potential circularity between comparative analyses of extinction risk and the IUCN criteria used to assess extinction risk[19]. Our conclusions on the role of high integrity forest fragments in playing a supporting role in biodiversity conservation also remained largely robust to the exclusion of criterion B species (Extended Data Figs. 3-5). However, the strength of the interactions between forest cover, integrity and condition diminished and some coefficients reversed in sign from positive to negative (95% CIs overlapped zero and FDR-adjusted $p > 0.05$ in 32 out of 48 models; Supplementary Tables 8-10). These findings suggest high integrity forests may be particularly important for species that are threatened because of restricted range area and forest fragmentation within these small ranges.

Human influence on the terrestrial biosphere is not limited to tropical rainforests but extends over much of Earth's land surface[21]. Therefore, future research needs to take advantage of global forest integrity[31] and ecosystem intactness[32] datasets to comprehensively quantify the importance of high integrity forest as well as non-forest ecosystems for biodiversity in all of the world's terrestrial biomes. Large-scale environmental perturbations such as climate change can interact with the many human pressures impacting forest systems and their biodiversity[33]. However, native high integrity forests are known to be more resilient to climate stressors than degraded forests. Large, contiguous, high integrity forest landscapes also provide connectivity across wide-ranging environmental gradients that can facilitate adaptive responses of species such as disperal to track shifting climate[13]. Consequently, the importance of the last remaining high integrity tropical rainforests for biodiversity conservation is likely to increase over time, given forests that are already degraded will likely experience intensifying pressures exacerbated by climate change[34].

Tropical rainforests harbor the overwhelming majority of the world's terrestrial biodiversity[15]. However, these hyperdiverse ecosystems are also under overwhelming human pressures worldwide[16–18], such that the accelerating trends in their loss and degradation predict a highly diminished and fragmented rainforest estate over the next few decades, depauperate in much of the biodiversity extant today and with limited ecosystem services for humanity[35]. We provide robust evidence of the global significance of native high integrity forests in mitigating species extinction risk, emphasizing the necessity to ensure conservation strategies aim to preserve and restore forest quality, as opposed to maintaining forest cover alone. A unique opportunity to advance biodiversity conservation is at hand, given 86% of the last remaining high integrity tropical rainforests remain unprotected[7]. Focusing conservation efforts on these imperiled ecosystems through environmental policies and management actions geared at their preservation will advance biodiversity conservation outcomes, particularly but not exclusively for threatened and restricted range species[7].

Our findings demonstrate a clear and urgent need for the targeted preservation of the last remaining high integrity forest landscapes in tandem with strategies aimed at protecting, restoring and reconnecting remnant forest fragments across the global humid tropics[7,27,28,36,37]. On the basis of the evidence presented here, we argue the single most important policy action nations can take to prevent catastrophic biodiversity loss in tropical rainforests is to commit to a global target of "no net loss in area and integrity" of these endangered ecosystems[38]. Such aggressive forest quality retention targets are urgently needed to 'bend the curve' on species loss in the Anthropocene[9,39], and ensure the CBD's post-2020 Global Biodiversity Framework stands a realistic chance "to put biodiversity on a path to recovery for the benefit of the planet and its people" by 2030[20].

Methods

No statistical methods were used to predetermine sample size. The experiments were not randomized and investigators were not blinded to allocation during experiments and outcome assessment.

Geographic range maps

We conducted our analyses across the tropical and subtropical moist broadleaf forest biome, which encompasses the present-day distribution of tropical rainforests around the Equator and between the Tropics of Cancer and Capricorn[23]. Despite covering a mere 14% of Earth's terrestrial area[23], these forests are home to over half of the world's vertebrate species[15], such that the continued loss and degradation of these imperilled ecosystems is likely to result in a disproportionately high number of extinctions. We followed the protocols in Pillay *et al*. (2021, *In press*)[15] to obtain the latest established geographic range maps for all species of mammals[22], birds[40], reptiles[41] and amphibians[22,42]. The original datasets contained range maps for 5,566 mammals, 11,125 birds, 10,064 reptiles and 6,684 amphibians, and include ranges for species that are extinct as well as polygons based on uncertain data.

We filtered all geographic range map datasets with three successive IUCN Red List of Threatened Species spatial attributes to remove extinct species and records based on uncertain data. First, we retained only species known to be "Extant", while discarding polygons representing parts of a species range where it was reported to be "Possibly extant", "Possibly extinct", "Extinct" and "Presence uncertain". Second, we filtered this list of extant species to retain only those that are "Native" and "Reintroduced", while discarding polygons representing parts of a species range where it was reported to be "Introduced", "Vagrant", "Origin uncertain" and "Assisted colonization". Third, we filtered the list of species from the second step above to retain only “Resident” and “Non-breeding” parts of the range for mammals (the only ones remaining for mammals after the first two filters above). For birds, we retained “Resident”, “Breeding”, “Non-breeding” and “Passage” parts of the range, while discarding “Seasonal occurrence uncertain”. For amphibians, we retained “Resident” parts of the range, which was the only one remaining after the first two filters above. The final list of amphibians from the IUCN Red List after this third filter included 6,607 species. However, this list of amphibians from the IUCN do not comprise all known species. Therefore, we included range maps for 659 additional amphibian species from González-del-Pliego *et al*. (2019)[42], after cross-verification to omit synonyms and extinct species. Because we obtained the reptile database from a source other than the IUCN Red List [41], we were unable to perform the same suite of filters on reptiles. However, our analyses showed that 10 species from this list are now regarded as extinct. Therefore, we discarded these 10 species. After performing these filters, our list of species for subsequent analyses included 5,529 mammals, 10,935 birds, 10,054 reptiles and 7,264 amphibians, for a total of 33,782 species of extant terrestrial vertebrates worldwide.

We projected all geographic range maps to the World Mollweide projection prior to analyses, and used Python code implemented with the ArcPy module in ArcGIS Pro 2.5.0 to perform a union of the range map of each species with the map of the tropical rainforest biome. This procedure allowed us to distinguish parts of the global range of species that overlap the tropical rainforest biome, should there be such overlap for a given species. Thereafter, we used species-level attributes from the IUCN Red List of Threatened Species to obtain data on the major habitats in which each species occurs to limit some forms of commission or false positive errors that may occur with range maps. Specifically, these errors include species whose ranges may overlap with the tropical rainforest biome but do not actually use the forests within that biome[15].

For species having range overlap with the tropical rainforest biome, we retained only species reported to occur in the tropical rainforest habitat types listed in the IUCN Habitats Classification Scheme[43]. We merged this list of species reported to occur in tropical rainforest habitats with the list of species whose ranges overlap the tropical rainforest biome to retain 3,327 mammals, 7,704 birds, 3,828 reptiles and 5,298 amphibians, for a total of 20,157 species with both range overlap and habitat association with tropical rainforests[15]. We note that we discarded additional species from this dataset on the basis of matching species names with those in the respective phylogenetic trees (for the final list of species in this study, see Statistical analyses).

Definiton of tropical rainforest endemic species

We defined endemism to tropical rainforests on the basis of the criteria established by Pillay *et al*. (2021, *In press*)[15]. We considered a species to be endemic if (1) 80-100% of its global range overlapped with the tropical rainforest biome, and (2) it was near-exclusively reported from the tropical rainforest habitat types listed in the IUCN Habitats Classification Scheme[43]. We did not exclude wetlands, rocky and cave habitats from this second criterion, making the reasonable assumption that for species with > 80% range overlap with the tropical rainforest biome and nearly exclusively associated with rainforest habitats, these three other habitat types are likely to be within tropical rainforests (*e.g.* bats that roost in caves within rainforest habitats).

Tropical rainforest structural condition and integrity indices and forest cover

We used two indices of tropical rainforest quality in our analyses – the Structural Condition Index (SCI) and the Forest Structural Integrity Index (FSII)[6,7]. The SCI is a 30 m resolution raster dataset that identifies locations of taller, older, more structurally complex, closed-canopy rainforests across the humid tropics. It is derived from canopy cover, canopy height and time since forest loss, and quantifies canopy stature, cover and disturbance history. The reference year is 2013, with canopy cover from 2010, forest loss expressed as year of loss before 2018 and canopy height for 2012. The SCI ranges from 1 to 18, with the lowest value delineating stands < 5 m tall, disturbed since 2012 or with canopy cover < 25%. The highest value represents tall, closed-canopy stands undisturbed since 2000. The FSII is derived by overlaying the Human Footprint (HFP), a 1 km resolution measure of the cumulative, in-situ pressures humans exert on natural areas across terrestrial Earth[21], on the SCI. The original 1993 HFP[44] was updated to 2009[45], and more recently to 2013[21]. The FSII ranges from 0.1 to 18 with the higher values representing rainforests high in structural complexity and low in human pressure. For complete details on the SCI and FSII indices, see Hansen *et al*. 2019[6], 2020[7].

As with the range maps, we projected the SCI and FSII rasters to the World Mollweide projection prior to analyses. Given the differing resolutions of the SCI and FSII rasters, (30 m and 1 km, respectively), we first made them comparable by resampling both to 1 km resolution using bilinear interpolation in ArcGIS 10.7. After resampling, the SCI raster comprised 1 km resolution pixels of values ranging from 1 to 18. We also converted the continuous pixel values of the FSII dataset to the nearest integer, such that the resampled FSII raster comprised 1 km resolution pixels of values ranging from 0 to 18. A relatively fine analytical resolution such as used here facilitates the efficient identification of forest cover and structurally intact and high integrity forests within species ranges and is recommended when the objective is to distinguish the effects of such broad habitat categories on biodiversity[46].

We then used Python code implemented with the ArcPy module in ArcGIS Pro 2.5.0 to calculate the area (km^2) of each of the 18 pixel values of the SCI and 19 pixel values of the FSII rasters within the humid tropical range of each species. Following the criteria established by

Hansen *et al*. 2020[7], we pooled and categorized the area of SCI values ranging from 2 to 5 (> 25% canopy cover and > 5 m canopy height) as low SCI or structurally degraded forest, and the area of SCI values ranging from 14 to 18 (> 75% canopy cover and > 15 m canopy height) as high SCI or structurally intact forest. We note some secondary and selectively logged forests have structural attributes similar to this high SCI class. When validating the SCI dataset, it was observed ~20% of older secondary forests were within the high SCI class[6]. Older secondary forests may not have all the structural intactness characteristics associated with forests that have never undergone anthropogenic degradation. However, current remote sensing capabilities do not allow discriminating these older secondary forests from unlogged native forests. Overall, the high SCI forests in our data are largely representative of structurally intact native forests typical of the humid tropics[7]. We followed a similar procedure to pool and categorize the area of FSII values ranging from 1 to 5 as low FSII or low integrity forest and the area of FSII values ranging from 14 to 18 as high FSII or high integrity forest. These high integrity forests represent rainforests of not only intact structural condition but also low human pressures, specifically HFP values ≤ 4[7].

Predictor variables

We calculated the relative difference between the area under high and low SCI forest within the humid tropical range of a species as: $\frac{area_{high\ SCI} - area_{low\ SCI}}{area_{humid\ tropical\ forest\ cover}}$. Similarly, we calculated the relative difference between the area under high and low FSII forest within the humid tropical range of a species as: $\frac{area_{high\ FSII} - area_{low\ FSII}}{area_{humid\ tropical\ forest\ cover}}$. These calculated values range between -1 and + 1 and represent the relative percentage difference between the area under high and low SCI and FSII forests within the humid tropical range of a species. Therefore, a value of -1 signifies 100%

of the humid tropical range of a species is encompassed by low SCI or low FSII forest, whereas a value of + 1 means 100% of the humid tropical range of a species is covered in high SCI or high FSII forest.

We also calculated the relative difference between the area of forest and non-forest cover within the humid tropical range of a species as: $\frac{area_{forest} - area_{non-forest}}{area_{humid\ tropical\ range}}$. We used the lowest SCI value of 1 to identify stands < 5 m tall, disturbed since 2012 or with canopy cover < 25%, which are considered highly disturbed, and categorized the area under this pixel value as non-forest[7]. We pooled and categorized the remaining SCI values from 2 to 18 as forest. Similar to the SCI and FSII relative difference values, these calculated values of forest cover also range between -1 (signifying 100% of the humid tropical range of a species consists of non-forest) and + 1 (signifying 100% of the humid tropical range of a species is forested). We thereby brought all forest cover, condition and integrity data (the predictor variables in this study) to a consistent scale for further analyses.

Statistical analyses

The response variables in this study are binary – threatened/non-threatened and declining population/not declining in population. To achieve this binary classification, we defined species in the IUCN Critically Endangered, Endangered and Vulnerable categories as threatened and species in the Near Threatened and Least Concern categories as non-threatened, while discarding species in the Data deficient category. With respect to the IUCN population trend data, we defined species in the Decreasing category as declining in population and species in the Increasing and Stable categories as not declining in population, while discarding species in the Unknown category[19].

We used a generalized linear modeling framework, specifically logistic regression, for statistical inference. Our primary units of analyses – species – cannot be considered as independent because of the variable degree of evolutionary relatedness between the species in each taxonomic group. To account for the potential effect of evolutionary dependence, we first obtained phylogenetic trees for mammals[47], birds[48], reptiles[49] and amphibians[50], and matched the species lists from the previous steps to discard species not in the respective phylogenetic trees. Our list of species after this step comprised 3,217 mammals, 6,674 birds, 3,735 reptiles and 5,069 amphibians, for a total of 18,695 species of vertebrates. We further discarded 2,299 Data deficient species for a final total of 16,396 species in the analyses of threatened status. We also discarded 5,842 species of Unknown population trend for a final total of 12,853 species in the analyses of declining population (Supplementary Table 1). For each taxonomic group, we partitioned species into rainforest endemic and non-endemic groups. Next, we randomly sampled 100 trees out of 10,000 available full phylogenetic trees for each taxonomic group, as recommended by Jetz *et al*. (2012)[48], to construct covariance matrices enumerating the proportion of the evolutionary path shared between each pair of species. We used these covariance matrices in phylogenetic logistic regression models to generate inferences corrected for phylogenetic signal[24].

We parameterized identical models for endemic and non-endemic species in each taxonomic group to test whether greater area of high integrity forests within species ranges is linked to a reduced odds of species: (i) being threatened, and (ii) having a declining population, relative to greater area of structurally intact forests and forest cover alone. Prior to analyses, we standardized each predictor variable (forest cover, condition and integrity) to have a mean of 0 and a standard deviation of 1 (z-transformation). We tested for the effects of the three predictor variables on the respective response variable (threatened status or declining population) by parameterizing them as additive effects in multiple phylogenetic logistic regression models, and used the standardized partial coefficient of each predictor variable as a measure of its effect on the response variable[19,25]. In this form of multiple logistic regression, the exponentiated standardized partial coefficient of a given predictor variable represents the odds of a 1-unit increase in that variable on the response, controlling for the effects of the other predictor variables by statistically holding them at their average values[25]. Given the highly correlated nature of the three predictor variables, standardized partial regression coefficients provide unbiased estimates of the relative importance of forest cover, condition and integrity forest on the odds of species being threatened or having a declining population[26]. We estimated 95% confidence intervals for the estimated standardized coefficients in each regression with 2,000 parametric bootstraps as recommended by Ives and Garland (2010)[24], and made inferences based on the median of 100 regressions, each regression being performed with one phylogenetic tree randomly drawn from 10,000 available trees[48]. Further, we tested for interactions between forest cover and integrity, forest condition and integrity, and forest cover and condition by incorporating two-way interactions between each of the above pairs of predictor variables in phylogenetic logistic regression models. Interaction models were otherwise parameterized in an identical manner to the additive models above.

We implemented phylogenetic logistic regression analyses via the package phylolm[51] in the R (v. 4.0.3) statistical programming language[52]. To limit bias in maximum likelihood estimates of logistic regression coefficients, we used the maximum penalized likelihood method with Firth's correction implemented in the phyloglm function via the parameter "logistic_MPLE"[24,51]. We conducted our analyses across thousands of species with three predictor variables in the case of additive models and two predictor variables for interaction models, which risks inflating type 1 error rate. Therefore, we used a FDR procedure (graphically sharpened method[53]) which corrects for multiple comparisons in comparative extinction risk modeling. We calculated FDR-adjusted *p*-values with the p.adjust function in R[54].

Influence of phylogenetic correlation

In phylogenetic logistic regression, the parameter α measures the strength of the phylogenetic correlation. When $\alpha = 1$, evolution is approximately by Brownian motion on a given phylogeny, with $\alpha > 1$indicating lower phylogenetic correlations among species[24]. In most cases across all taxonomic groups and models, the estimated phylogenetic signal α was close to zero (Supplementary Tables 11-12), suggesting the predictor variables included in the models induced phylogenetic signal in the residuals.

Data availability

All datasets used in this paper are openly available via the citations identified in the Methods.

Code availability

Custom Python and R code used for geospatial and statistical analyses will be uploaded to GitHub/Zenodo upon acceptance.

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Author contributions

R.P. conceived the original idea for this study with major inputs from O.V., J.E.M.W., and A.J.H.; J.A.O. and R.P. developed the Python code for geospatial analyses; P.G.D.P. provided amphibian range maps not available in the IUCN Red List; R.P. performed all geospatial and statistical analyses and wrote the manuscript; O.V., J.E.M.W., A.J.H., S.J.G., P.J., P.B., C.S., D.A., B.A.W., P.G.D.P., J.A.O., S.C.A., J.E., and A.L.S.V. provided critical editorial inputs on manuscript drafts.

Additional information

Supplementary information is available for this paper and is appended below for peer-review.

Figure 1. Effects of forest cover, structural condition and integrity on the threatened status and declining population trend of tropical rainforest mammals, birds, reptiles and amphibians. Point estimates represent median standardized odds of species being threatened (circles) or having a declining population (squares) generated by exponentiating standardized coefficients (log odds) of 100 phylogenetic logistic regressions to obtain standardized odds ratios, and thereafter converting to percentage odds to aid interpretation. Each regression was performed with one phylogenetic tree randomly drawn from 10,000 available trees for each taxonomic group, and separate models were parameterized for rainforest endemic and non-endemic species for each response variable. Error bars represent median 95% confidence intervals generated with 2,000 parametric bootstraps in each regression. See Supplementary Tables 1-2 for sample sizes and model results, respectively.

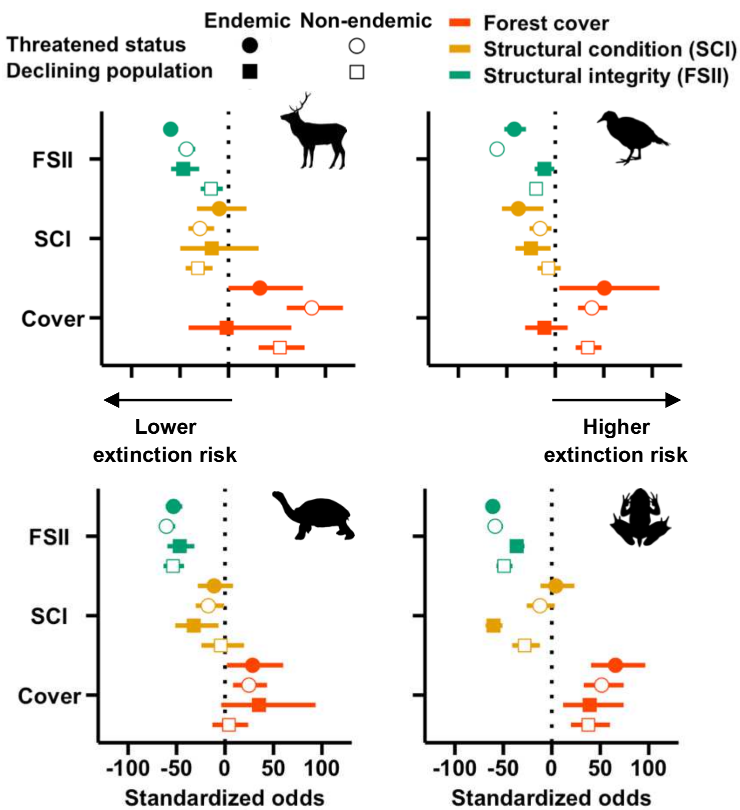


Figure 2. Predicted probabilities of mammals, birds, reptiles and amphibians being threatened or having declining populations as a function of forest cover area and the area of forests of varying integrity within species humid tropical ranges. Median predicted probabilities were generated from 100 phylogenetic logistic regressions. See Supplementary Tables 1 and 3 for sample sizes and model results, respectively.

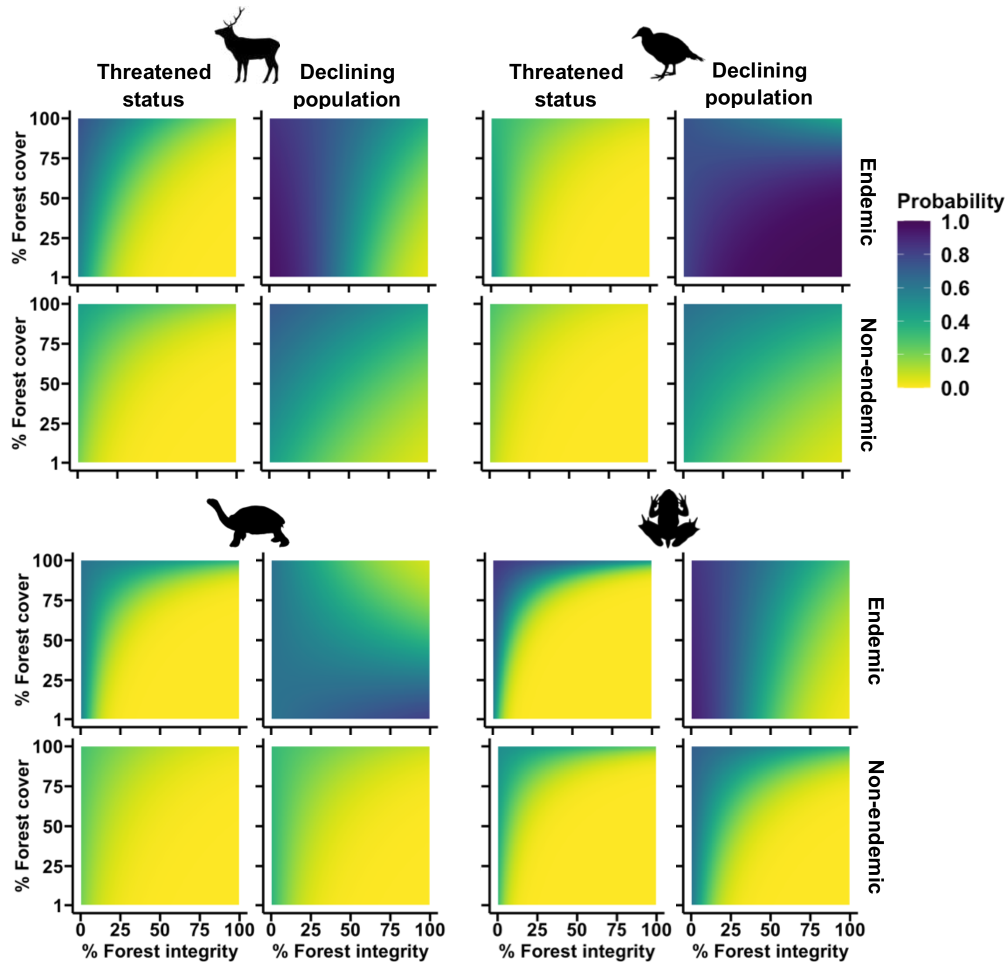
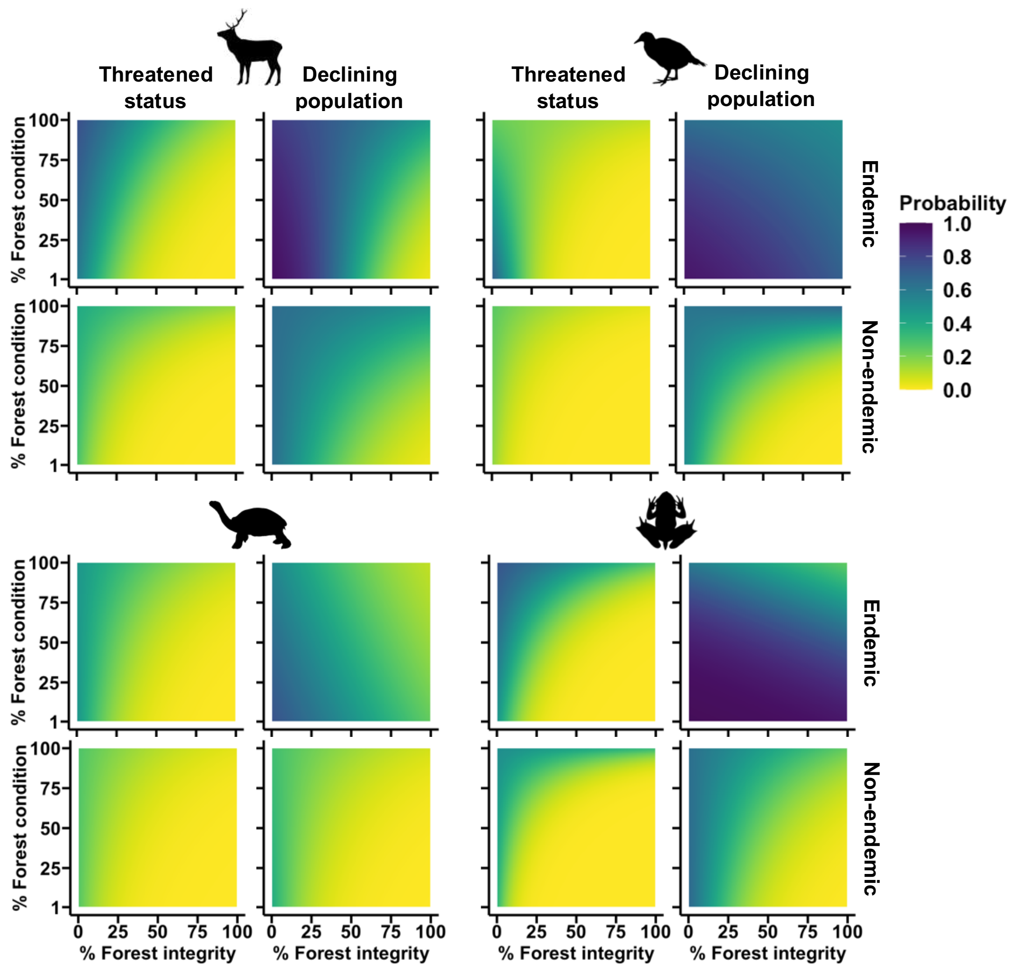
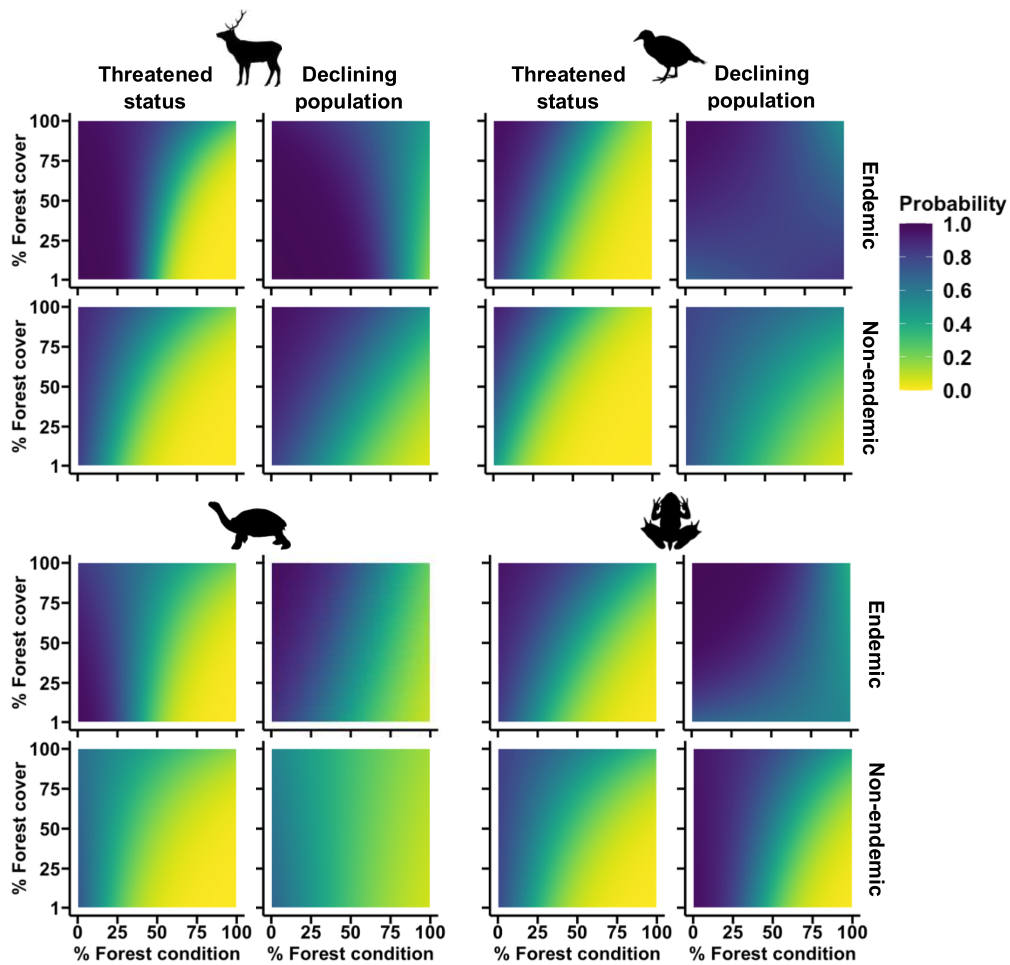


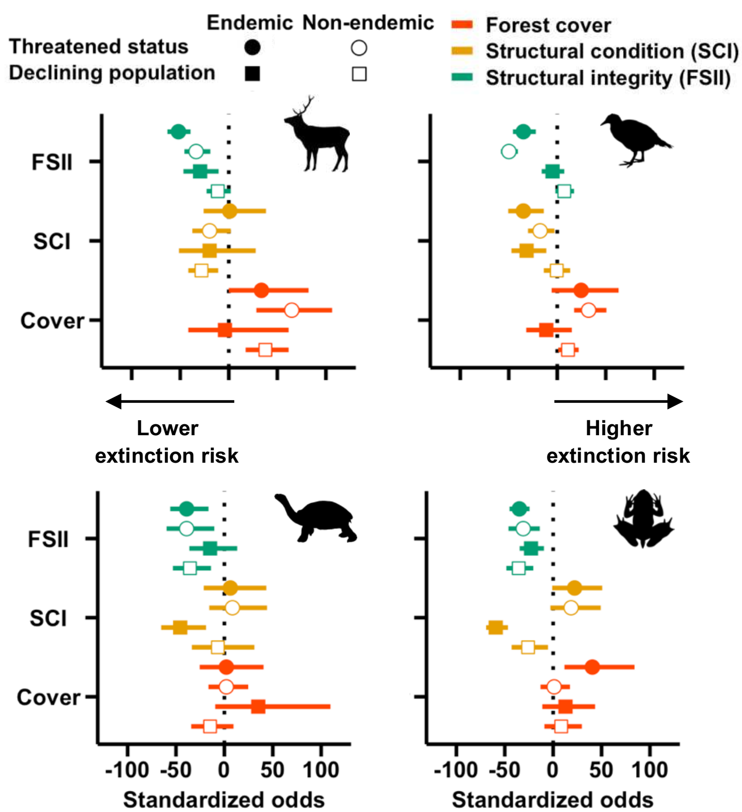
Figure 3. Predicted probabilities of mammals, birds, reptiles and amphibians being threatened or having declining populations as a function of the area under forests of varying condition and integrity within species humid tropical ranges. Median predicted probabilities were generated from 100 phylogenetic logistic regressions. See Supplementary Tables 1 and 4 for sample sizes and model results, respectively.



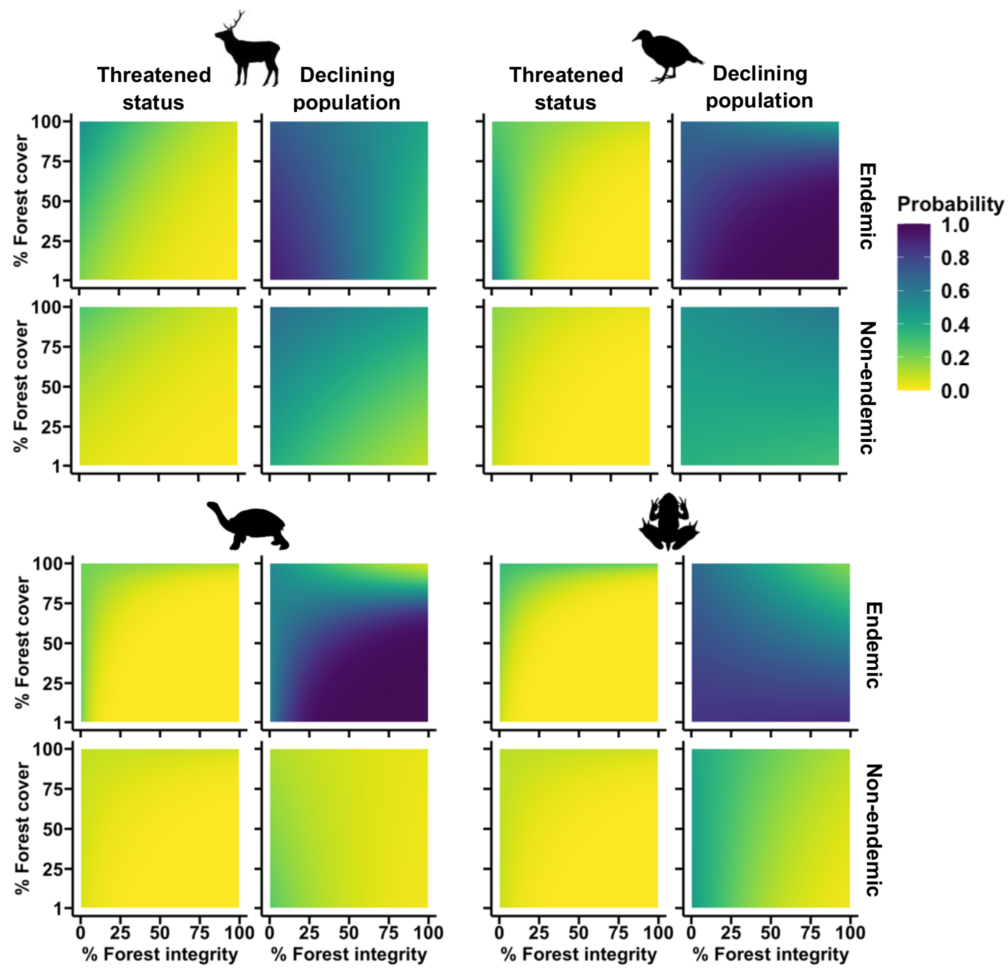
Extended Data Figure 1. Predicted probabilities of mammals, birds, reptiles and amphibians being threatened or having declining populations as a function of forest cover area and the area of forests of varying condition within species humid tropical ranges. Median predicted probabilities were generated from 100 phylogenetic logistic regressions. See Supplementary Tables 1 and 5 for sample sizes and model results, respectively.



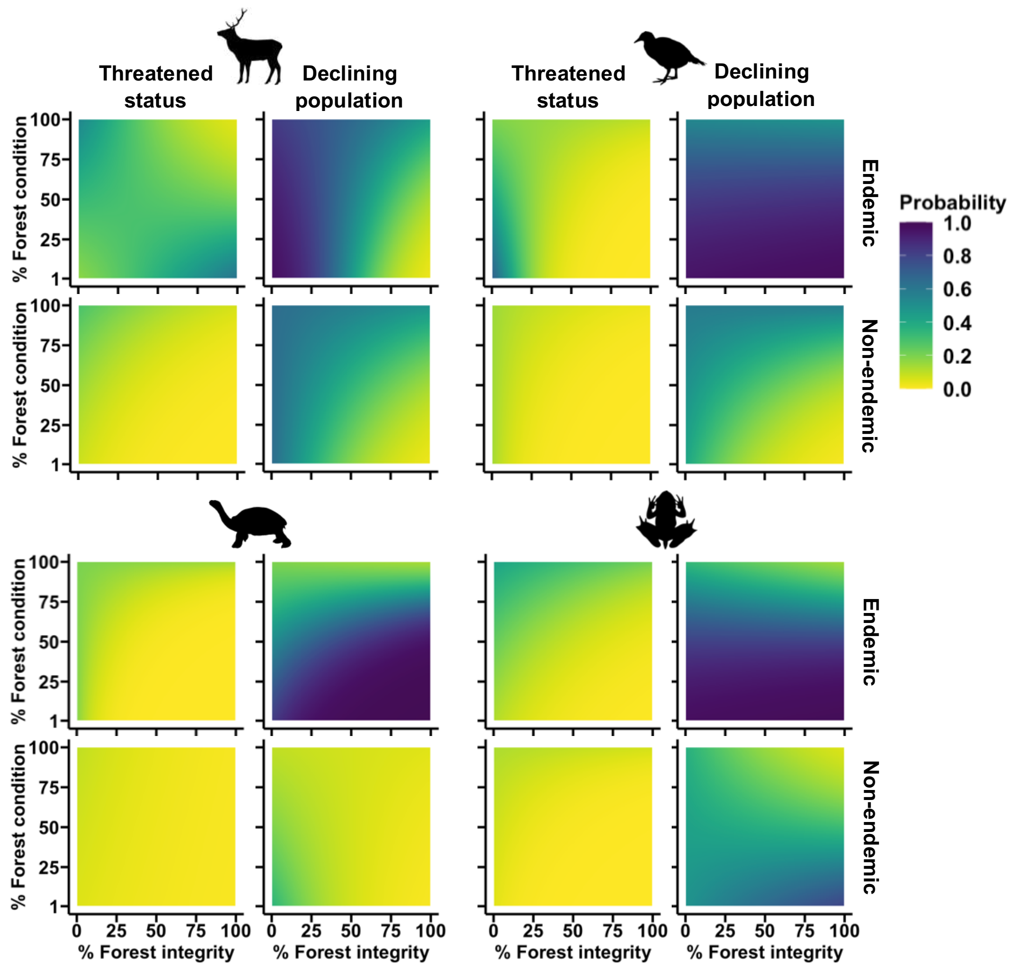
Extended Data Figure 2. Effects of forest cover, structural condition and integrity on the threatened status and declining population trend of tropical rainforest mammals, birds, reptiles and amphibians after excluding 2,751 and 2,155 species in IUCN criterion B for threatened status and declining population response variables, respectively. Point estimates represent median standardized odds of species being threatened (circles) or having a declining population (squares) generated by exponentiating standardized coefficients (log odds) of 100 phylogenetic logistic regressions to obtain standardized odds ratios, and thereafter converting to percentage odds to aid interpretation. Each regression was performed with one phylogenetic tree randomly drawn from 10,000 available trees for each taxonomic group, and separate models were parameterized for rainforest endemic and non-endemic species for each response variable. Error bars represent median 95% confidence intervals generated with 2,000 parametric bootstraps in each regression. See Supplementary Tables 6-7 for sample sizes and model results, respectively.



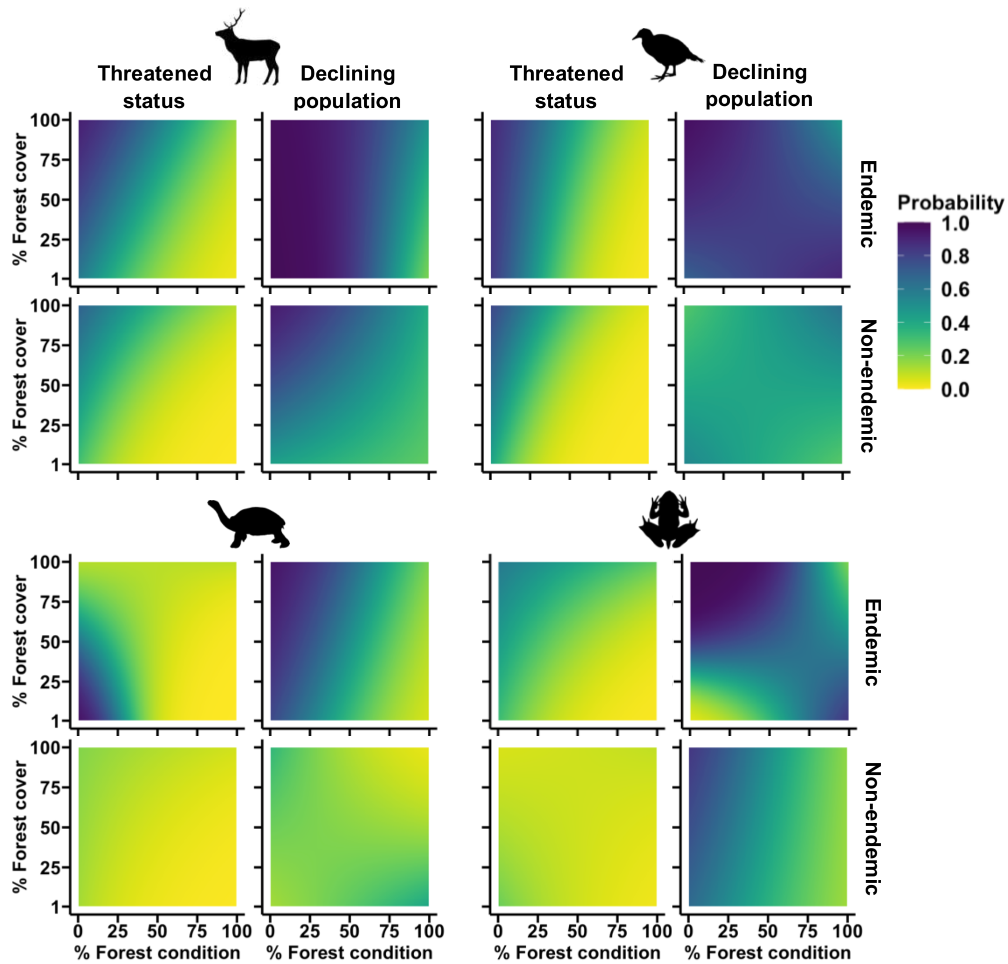
Extended Data Figure 3. Predicted probabilities of mammals, birds, reptiles and amphibians being threatened or having declining populations as a function of forest cover area and the area of forests of varying integrity within species humid tropical ranges. This analysis was performed after excluding 2,751 and 2,155 species in IUCN criterion B for threatened status and declining population response variables, respectively. Median predicted probabilities were generated from 100 phylogenetic logistic regressions. See Supplementary Tables 6 and 8 for samples sizes and model results, respectively.



Extended Data Figure 4. Predicted probabilities of mammals, birds, reptiles and amphibians being threatened and having declining populations as a function of the area of forests of varying condition and integrity within species humid tropical ranges. This analysis was performed after excluding 2,751 and 2,155 species in IUCN criterion B for threatened status and declining population response variables, respectively. Median predicted probabilities were generated from 100 phylogenetic logistic regressions. See Supplementary Tables 6 and 9 for sample sizes and model results, respectively.



Extended Data Figure 5. Predicted probabilities of mammals, birds, reptiles and amphibians being threatened and having declining populations as a function of forest cover area and the area of forests of varying condition within species humid tropical ranges. This analysis was performed after excluding 2,751 and 2,155 species in IUCN criterion B for threatened status and declining population response variables, respectively. Median predicted probabilities were generated from 100 phylogenetic logistic regressions. See Supplementary Tables 6 and 10 for sample sizes and model results, respectively.



Supplementary Table 1. Sample sizes in terms of the number of rainforest endemic and non-endemic species included in analyses for threatened status and declining population. There were a total of 18,695 species after geospatial analyses and matching species names in the IUCN Red List with those in the respective phylogenetic trees. Of these species, we discarded Data deficient and Unknown population trend categories for a final total of 16,396 species in the analyses of threatened status and 12,853 species in the analyses of declining population. We classified species in the IUCN Critically Endangered, Endangered and Vulnerable categories as threatened and species in Near Threatened and Least Concern categories as non-threatened. With respect to the IUCN population trend data, we classified species in the Decreasing category as declining in population and species in the Increasing and Stable categories as not declining in population. See Methods for details.

habitat	response variable	mammals	birds	reptiles	amphibians	total
endemic		971	1,588	1,307	2,586	6,452
non-endemic		2,246	5,086	2,428	2,483	12,243
total		**3,217**	**6,674**	**3,735**	**5,069**	**18,695**
endemic	threatened status	743	1,576	988	1,951	5,258
	declining population	513	1,522	397	1,676	4,108
non-endemic	threatened status	2,035	5,076	2,215	1,812	11,138
	declining population	1,338	4,725	1,240	1,442	8,745
total	threatened status	2,778	6,652	3,203	3,763	16,396
	declining population	1,851	6,247	1,637	3,118	12,853

Supplementary Table 2. Results of multiple phylogenetic logistic regression models contrasting the effects of forest cover, structural condition and integrity on the threatened status and declining population trend of humid tropical (a) mammals, (b) birds, (c) reptiles and (d) amphibians worldwide. Estimates represent median standardized coefficients (log odds) from 100 phylogenetic logistic regressions. The 95% confidence intervals of estimated coefficients were generated with 2,000 parametric bootstraps in each regression. Adj. *p*-value represents the False Discovery Rate (FDR)-adjusted *p*-value. We fit identical models separately for endemic and non-endemic species within each taxonomic group. Standardized coefficients generated by the models were exponentiated to obtain standardized odds ratios, and further converted to percentage odds using the formula $[e^{(\beta)} - 1] \times 100$ (Fig. 1).

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
a. Mammals						
threatened status	intercept	endemic	0.07	-0.28 – 0.41	0.62	1.00
	cover		0.28	0.00 – 0.57	0.08	0.11
	condition		-0.10	-0.40 – 0.17	0.51	0.74
	integrity		-0.91	-1.11 – -0.73	< 0.001	< 0.001
	intercept	non-endemic	-1.25	-1.45 – -1.07	< 0.001	< 0.001
	cover		0.62	0.47 – 0.78	< 0.001	< 0.001
	condition		-0.35	-0.54 – -0.16	< 0.001	< 0.001
	integrity		-0.57	-0.73 – -0.42	< 0.001	< 0.001
declining population	intercept	endemic	1.48	0.81 – 1.98	< 0.001	< 0.001
	cover		-0.02	-0.53 – 0.50	0.88	1.00
	condition		-0.19	-0.69 – 0.27	0.44	0.63
	integrity		-0.63	-0.90 – -0.36	< 0.001	< 0.001
	intercept	non-endemic	0.33	0.13 – 0.53	< 0.001	< 0.001
	cover		0.43	0.27 – 0.58	< 0.001	< 0.001
	condition		-0.38	-0.59 – -0.18	< 0.001	< 0.001
	integrity		-0.20	-0.34 – -0.06	0.01	0.01
b. Birds						
threatened status	intercept	endemic	-1.34	-1.57 – -0.47	< 0.001	< 0.001
	cover		0.41	0.04 – 0.73	< 0.001	< 0.001
	condition		-0.48	-0.80 – -0.13	< 0.001	< 0.001
	integrity		-0.55	-0.75 – -0.36	< 0.001	< 0.001
	intercept	non-endemic	-2.20	-2.40 – -2.00	< 0.001	< 0.001
	cover		0.32	0.21 – 0.43	< 0.001	< 0.001
	condition		-0.17	-0.31 – -0.04	0.03	0.05
	integrity		-0.92	-1.08 – -0.78	< 0.001	< 0.001
declining population	intercept	endemic	1.12	0.89 – 1.35	< 0.001	< 0.001
	cover		-0.12	-0.38 – 0.12	0.28	0.49
	condition		-0.29	-0.53 – -0.05	0.03	0.53
	integrity		-0.12	-0.24 – -0.01	0.07	0.13
	intercept	non-endemic	0.04	-0.05 – 0.12	0.42	0.81
	cover		0.29	0.19 – 0.39	< 0.001	< 0.001
	condition		-0.08	-0.21 – 0.06	0.14	0.27
	integrity		-0.22	-0.31 – -0.14	< 0.001	< 0.001

Supplementary Table 2 (continued).

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
c. Reptiles						
threatened status	intercept	endemic	-0.83	-1.10 – -0.56	< 0.001	< 0.001
	cover		0.25	0.02 – 0.47	0.05	0.08
	condition		-0.12	-0.33 – 0.08	0.29	0.54
	integrity		-0.76	-0.95 – -0.58	< 0.001	< 0.001
	intercept	non-endemic	-1.76	-1.97 – -1.57	< 0.001	< 0.001
	cover		0.22	0.08 – 0.36	0.01	0.02
	condition		-0.19	-0.36 – -0.01	0.06	0.12
	integrity		-0.93	-1.15 – -0.72	< 0.001	< 0.001
declining population	intercept	endemic	-0.04	-0.40 – 0.33	0.81	1.00
	cover		0.30	-0.04 – 0.66	0.10	0.14
	condition		-0.39	-0.72 – -0.07	0.03	0.04
	integrity		-0.63	-0.91 – -0.38	< 0.001	< 0.001
	intercept	non-endemic	-1.29	-1.52 – -1.08	< 0.001	< 0.001
	cover		0.04	-0.14 – 0.22	0.73	0.99
	condition		-0.05	-0.28 – 0.18	0.70	1.00
	integrity		-0.77	-1.01 – -0.55	< 0.001	< 0.001
d. Amphibians						
threatened status	intercept	endemic	0.44	0.23 – 0.65	0.02	0.04
	cover		0.51	0.34 – 0.68	< 0.001	< 0.001
	condition		0.04	-0.13 – 0.21	0.61	0.98
	integrity		-0.94	-1.06 – -0.82	< 0.001	< 0.001
	intercept	non-endemic	-0.90	-1.11 – -0.70	< 0.001	< 0.001
	cover		0.42	0.29 – 0.56	< 0.001	< 0.001
	condition		-0.13	-0.30 – 0.03	0.16	0.30
	integrity		-0.88	-1.07 – -0.70	< 0.001	< 0.001
declining population	intercept	endemic	1.17	0.92 – 1.43	< 0.001	< 0.001
	cover		0.33	0.11 – 0.56	0.01	0.01
	condition		-0.92	-1.15 – -0.71	< 0.001	< 0.001
	integrity		-0.45	-0.57 – -0.33	< 0.001	< 0.001
	intercept	non-endemic	0.05	-0.17 – 0.26	0.72	1.00
	cover		0.32	0.18 – 0.47	< 0.001	< 0.001
	condition		-0.33	-0.53 – -0.13	< 0.001	< 0.001
	integrity		-0.68	-0.85 – -0.52	< 0.001	< 0.001

Supplementary Table 3. Results of phylogenetic logistic regression models testing for interactions between forest cover and integrity on the threatened status and declining population trend of humid tropical (a) mammals, (b) birds, (c) reptiles and (d) amphibians worldwide. Estimates represent median standardized beta coefficients (log odds) from 100 phylogenetic logistic regressions. The 95% confidence intervals of estimated coefficients were generated with 2,000 parametric bootstraps in each regression. Adj. *p*-value represents the False Discovery Rate (FDR)-adjusted *p*-value. We fit identical models separately for endemic and non-endemic species within each taxonomic group. See Fig. 2 for predicted probabilities generated from these results.

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
a. Mammals						
threatened status	intercept	endemic	-0.29	-0.69 – 0.12	0.35	0.68
	cover		0.52	0.22 – 0.82	< 0.001	< 0.001
	integrity		-1.34	-1.75 – -0.94	< 0.001	< 0.001
	cover × integrity		0.38	0.02 – 0.77	0.08	0.13
	intercept	non-endemic	-1.41	-1.64 – -1.19	< 0.001	< 0.001
	cover		0.64	0.47 – 0.81	< 0.001	< 0.001
	integrity		-1.04	-1.26 – -0.84	< 0.001	< 0.001
	cover × integrity		0.47	0.27 – 0.68	< 0.001	< 0.001
declining population	intercept	endemic	1.38	0.76 – 1.92	< 0.001	< 0.001
	cover		-0.07	-0.49 – 0.33	0.71	0.99
	integrity		-0.90	-1.39 – -0.44	< 0.001	< 0.001
	cover × integrity		0.23	-0.21 – 0.68	0.36	0.61
	intercept	non-endemic	0.29	0.07 – 0.50	0.01	0.01
	cover		0.31	0.18 – 0.44	< 0.001	< 0.001
	integrity		-0.44	-0.59 – -0.29	< 0.001	< 0.001
	cover × integrity		0.09	-0.06 – 0.24	0.33	0.58
b. Birds						
threatened status	intercept	endemic	-1.59	-1.97 – -1.23	< 0.001	< 0.001
	cover		0.36	0.06 – 0.68	< 0.001	< 0.001
	integrity		-1.23	-1.67 – -0.81	< 0.001	< 0.001
	cover × integrity		0.51	0.16 – 0.89	< 0.001	< 0.001
	intercept	non-endemic	-2.42	-2.68 – -2.16	< 0.001	< 0.001
	cover		0.64	0.46 – 0.81	< 0.001	< 0.001
	integrity		-1.32	-1.54 – -1.10	< 0.001	< 0.001
	cover × integrity		0.47	0.28 – 0.68	< 0.001	< 0.001
declining population	intercept	endemic	1.24	1.03 – 1.49	< 0.001	< 0.001
	cover		-0.39	-0.57 – -0.21	< 0.001	< 0.001
	integrity		0.10	-0.13 – 0.34	0.31	0.56
	cover × integrity		-0.35	-0.55 – -0.15	< 0.001	< 0.001
	intercept	non-endemic	-0.02	-0.12 – 0.08	0.49	0.90
	cover		0.28	0.21 – 0.36	< 0.001	< 0.001
	integrity		-0.33	-0.42 – -0.25	< 0.001	< 0.001
	cover × integrity		0.10	0.02 – 0.18	0.02	0.04

Supplementary Table 3 (continued).

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
c. Reptiles						
threatened status	intercept	endemic	-0.86	-1.17 – -0.55	< 0.001	< 0.001
	cover		0.89	0.67 – 1.08	< 0.001	< 0.001
	integrity		-1.76	-2.02 – -1.42	< 0.001	< 0.001
	cover × integrity		1.14	0.86 – 1.36	< 0.001	< 0.001
	intercept	non-endemic	-1.87	-2.11 – -1.64	< 0.001	< 0.001
	cover		0.42	0.20 – 0.65	< 0.001	< 0.001
	integrity		-1.18	-1.46 – -0.93	< 0.001	< 0.001
	cover × integrity		0.43	0.13 – 0.72	< 0.001	< 0.001
declining population	intercept	endemic	0.14	-0.31 – 0.60	0.60	0.88
	cover		-0.17	-0.58 – 0.20	0.42	0.67
	integrity		-0.51	-1.04 – 0.00	0.10	0.16
	cover × integrity		-0.24	-0.78 – 0.27	0.43	0.63
	intercept	non-endemic	-1.41	-1.67 – -1.16	< 0.001	< 0.001
	cover		0.31	0.07 – 0.54	0.01	0.01
	integrity		-0.99	-1.28 – -0.72	< 0.001	< 0.001
	cover × integrity		0.45	0.13 – 0.76	< 0.001	< 0.001
d. Amphibians						
threatened status	intercept	endemic	-0.29	-0.51 – -0.05	0.15	0.29
	cover		1.62	1.42 – 1.79	< 0.001	< 0.001
	integrity		-2.38	-2.58 – -2.10	< 0.001	< 0.001
	cover × integrity		1.87	1.60 – 2.08	< 0.001	< 0.001
	intercept	non-endemic	-1.35	-1.58 – -1.07	< 0.001	< 0.001
	cover		1.17	0.90 – 1.39	< 0.001	< 0.001
	integrity		-1.78	-2.05 – -1.46	< 0.001	< 0.001
	cover × integrity		1.42	1.04 – 1.72	< 0.001	< 0.001
declining population	intercept	endemic	1.16	0.92 – 1.40	< 0.001	< 0.001
	cover		0.03	-0.19 – 0.24	0.70	0.99
	integrity		-1.05	-1.30 – -0.79	< 0.001	< 0.001
	cover × integrity		0.22	-0.07 – 0.51	0.20	0.33
	intercept	non-endemic	-0.08	-0.32 – 0.16	0.58	0.95
	cover		0.63	0.45 – 0.82	< 0.001	< 0.001
	integrity		-1.19	-1.42 – -0.98	< 0.001	< 0.001
	cover × integrity		0.77	0.52 – 1.02	< 0.001	< 0.001

Notes – A positive coefficient for the interaction term would suggest that the effect of forest integrity on the response variable is stronger when small amounts of high integrity (*i.e.,* structurally intact *and* low pressure) forest remain within species humid tropical ranges, as opposed to when large extents are forested but of low integrity. In contrast, a negative coefficient for the interaction term would indicate that the effect of forest integrity on the response variable is stronger when large extents of high integrity forest remain within species ranges, as opposed to small fragments, irrespective of integrity.

Supplementary Table 4. Results of phylogenetic logistic regression models testing for interactions between rainforest structural condition and integrity on the threatened status and declining population trend of humid tropical (a) mammals, (b) birds, (c) reptiles and (d) amphibians worldwide. Estimates represent median standardized coefficients (log odds) from 100 phylogenetic logistic regressions. 95% confidence intervals of estimated coefficients were generated with 2,000 parametric bootstraps in each regression. Adj. *p*-value represents the False Discovery Rate (FDR)-adjusted *p*-value. We fit identical models separately for endemic and non-endemic species within each taxonomic group. See Fig. 3 for predicted probabilities generated from these results.

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
a. Mammals						
threatened status	intercept	endemic	-0.15	-0.53 – 0.21	0.64	0.94
	condition		0.28	0.04 – 0.54	0.06	0.08
	integrity		-1.20	-1.57 – -0.85	< 0.001	< 0.001
	condition × integrity		0.18	-0.07 – 0.44	0.25	0.37
	intercept	non-endemic	-1.44	-1.66 – -1.21	< 0.001	< 0.001
	condition		0.38	0.21 – 0.56	< 0.001	< 0.001
	integrity		-1.00	-1.24 – -0.77	< 0.001	< 0.001
	condition × integrity		0.35	0.18 – 0.51	< 0.001	< 0.001
declining population	intercept	endemic	1.32	0.63 – 1.84	< 0.001	< 0.001
	condition		-0.09	-0.45 – 0.29	0.61	1.00
	integrity		-0.92	-1.44 – -0.44	< 0.001	< 0.001
	condition × integrity		0.23	-0.10 – 0.56	0.20	0.36
	intercept	non-endemic	0.19	-0.03 – 0.41	0.09	0.17
	condition		0.14	0.00 – 0.30	0.09	0.17
	integrity		-0.48	-0.67 – -0.29	< 0.001	< 0.001
	condition × integrity		0.16	0.04 – 0.30	0.02	0.04
b. Birds						
threatened status	intercept	endemic	-1.55	-1.89 – -1.21	< 0.001	< 0.001
	condition		0.04	-0.30 – 0.36	0.24	0.46
	integrity		-1.02	-1.49 – -0.49	< 0.001	< 0.001
	condition × integrity		0.37	0.04 – 0.68	< 0.001	< 0.001
	intercept	non-endemic	-2.49	-2.75 – -2.22	< 0.001	< 0.001
	condition		0.45	0.29 – 0.63	< 0.001	< 0.001
	integrity		-1.33	-1.58 – -1.12	< 0.001	< 0.001
	condition × integrity		0.39	0.24 – 0.56	< 0.001	< 0.001
declining population	intercept	endemic	1.01	0.78 – 1.25	< 0.001	< 0.001
	condition		-0.29	-0.47 – -0.13	< 0.001	< 0.001
	integrity		-0.26	-0.51 – -0.01	0.14	0.28
	condition × integrity		0.06	-0.10 – 0.23	0.60	0.97
	intercept	non-endemic	-0.20	-0.30 – -0.10	< 0.001	< 0.001
	condition		0.36	0.27 – 0.46	< 0.001	< 0.001
	integrity		-0.57	-0.69 – -0.45	< 0.001	< 0.001
	condition × integrity		0.32	0.24 – 0.39	< 0.001	< 0.001

Supplementary Table 4 (continued).

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
c. Reptiles						
threatened status	intercept	endemic	-0.81	-1.10 – -0.51	< 0.001	< 0.001
	condition		0.15	-0.06 – 0.36	0.18	0.33
	integrity		-0.97	-1.33 – -0.64	< 0.001	< 0.001
	condition × integrity		0.21	-0.04 – 0.44	0.09	0.17
	intercept	non-endemic	-1.77	-2.01 – -1.53	< 0.001	< 0.001
	condition		0.19	0.01 – 0.38	0.03	0.06
	integrity		-1.05	-1.31 – -0.80	< 0.001	< 0.001
	condition × integrity		0.24	0.02 – 0.47	0.02	0.04
declining population	intercept	endemic	0.03	-0.42 – 0.45	0.85	0.99
	condition		-0.17	-0.47 – 0.17	0.40	0.73
	integrity		-0.61	-1.16 – -0.15	0.02	0.03
	condition × integrity		-0.01	-0.35 – 0.37	0.86	1.00
	intercept	non-endemic	-1.37	-1.64 – -1.12	< 0.001	< 0.001
	condition		0.10	-0.11 – 0.32	0.33	0.53
	integrity		-0.90	-1.20 – -0.62	< 0.001	< 0.001
	condition × integrity		0.22	-0.02 – 0.46	0.06	0.10
d. Amphibians						
threatened status	intercept	endemic	-0.28	-0.50 – -0.04	0.10	0.18
	condition		0.55	0.38 – 0.72	< 0.001	< 0.001
	integrity		-1.40	-1.66 – -1.15	< 0.001	< 0.001
	condition × integrity		0.49	0.30 – 0.68	< 0.001	< 0.001
	intercept	non-endemic	-1.35	-1.59 – -1.08	< 0.001	< 0.001
	condition		0.77	0.57 – 0.96	< 0.001	< 0.001
	integrity		-1.71	-2.02 – -1.39	< 0.001	< 0.001
	condition × integrity		0.92	0.68 – 1.15	< 0.001	< 0.001
declining population	intercept	endemic	1.20	0.94 – 1.48	< 0.001	< 0.001
	condition		-0.72	-0.89 – -0.54	< 0.001	< 0.001
	integrity		-0.47	-0.71 – -0.22	< 0.001	< 0.001
	condition × integrity		0.01	-0.20 – 0.21	0.79	1.00
	intercept	non-endemic	-0.07	-0.32 – 0.17	0.63	0.99
	condition		0.16	-0.01 – 0.34	0.11	0.21
	integrity		-0.93	-1.19 – -0.69	< 0.001	< 0.001
	condition × integrity		0.26	0.06 – 0.47	0.02	0.04

Notes – A positive coefficient for the interaction term would suggest that the effect of forest integrity on the response variable is stronger when small amounts of high integrity (*i.e.,* structurally intact *and* low pressure) forest remain within species humid tropical ranges, as opposed to when large extents are structurally intact but of low integrity (*i.e.* high human pressure). In contrast, a negative coefficient for the interaction term would indicate that the effect of forest condition on the response variable is stronger when large extents of high integrity forest remain within species humid tropical ranges, as opposed to small fragments, irrespective of integrity.

Supplementary Table 5. Results of phylogenetic logistic regression models testing for interactions between forest cover and rainforest structural condition on the threatened status and declining population trend of humid tropical (a) mammals, (b) birds, (c) reptiles and (d) amphibians worldwide. Estimates represent median standardized coefficients (log odds) from 100 phylogenetic logistic regressions. 95% confidence intervals of estimated coefficients were generated with 2,000 parametric bootstraps in each regression. Adj. *p*-value represents the False Discovery Rate (FDR)-adjusted *p*-value. We fit identical models separately for endemic and non-endemic species within each taxonomic group. See Extended Data Fig. 1 for predicted probabilities generated from these results.

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
a. Mammals						
threatened status	intercept	endemic	-0.57	-0.87 – -0.19	< 0.001	< 0.001
	cover		0.85	0.53 – 1.19	< 0.001	< 0.001
	condition		-1.22	-1.63 – -0.90	< 0.001	< 0.001
	cover × condition		0.37	0.14 – 0.55	< 0.001	< 0.001
	intercept	non-endemic	-1.50	-1.70 – -1.30	< 0.001	< 0.001
	cover		0.89	0.69 – 1.10	< 0.001	< 0.001
	condition		-0.83	-1.02 – -0.65	< 0.001	< 0.001
	cover × condition		0.18	0.10 – 0.27	< 0.001	< 0.001
declining population	intercept	endemic	0.91	0.41 – 1.39	< 0.001	< 0.001
	cover		-0.16	-0.57 – 0.25	0.43	0.80
	condition		-0.80	-1.13 – -0.42	< 0.001	< 0.001
	cover × condition		0.23	-0.10 – 0.38	0.13	0.20
	intercept	non-endemic	0.29	0.06 – 0.50	0.01	0.02
	cover		0.53	0.36 – 0.71	< 0.001	< 0.001
	condition		-0.60	-0.78 – -0.42	< 0.001	< 0.001
	cover × condition		0.04	-0.03 – 0.13	0.33	0.58
b. Birds						
threatened status	intercept	endemic	-1.36	-1.59 – -1.12	< 0.001	< 0.001
	cover		0.64	0.21 – 1.01	< 0.001	< 0.001
	condition		-0.97	-1.29 – -0.63	< 0.001	< 0.001
	cover × condition		0.06	-0.04 – 0.19	0.17	0.32
	intercept	non-endemic	-2.42	-2.58 – -2.26	< 0.001	< 0.001
	cover		0.89	0.71 – 1.07	< 0.001	< 0.001
	condition		-0.92	-1.08 – -0.76	< 0.001	< 0.001
	cover × condition		0.09	0.03 – 0.14	< 0.001	< 0.001
declining population	intercept	endemic	1.20	0.96 – 1.45	< 0.001	< 0.001
	cover		-0.08	-0.32 – 0.17	0.40	0.77
	condition		-0.38	-0.60 – -0.17	< 0.001	< 0.001
	cover × condition		-0.14	-0.20 – -0.06	< 0.001	< 0.001
	intercept	non-endemic	-0.07	-0.16 – 0.02	0.15	0.28
	cover		0.42	0.31 – 0.53	< 0.001	< 0.001
	condition		-0.31	-0.41 – -0.21	< 0.001	< 0.001
	cover × condition		0.08	0.04 – 0.13	< 0.001	< 0.001

Supplementary Table 5 (continued).

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
c. Reptiles						
threatened status	intercept	endemic	-1.06	-1.32 – -0.78	< 0.001	< 0.001
	cover		0.59	0.32 – 0.88	< 0.001	< 0.001
	condition		-0.87	-1.18 – -0.60	< 0.001	< 0.001
	cover × condition		0.28	0.11 – 0.50	< 0.001	< 0.001
	intercept	non-endemic	-1.78	-1.97 – -1.59	< 0.001	< 0.001
	cover		0.73	0.54 – 0.92	< 0.001	< 0.001
	condition		-0.65	-0.83 – -0.48	< 0.001	< 0.001
	cover × condition		0.22	0.13 – 0.31	< 0.001	< 0.001
declining population	intercept	endemic	0.00	-0.36 – 0.37	0.80	1.00
	cover		0.32	-0.03 – 0.69	0.09	0.15
	condition		-0.79	-1.15 – -0.47	< 0.001	< 0.001
	cover × condition		-0.02	-0.19 – 0.25	0.81	1.00
	intercept	non-endemic	-1.24	-1.46 – -1.04	< 0.001	< 0.001
	cover		0.08	-0.13 – 0.29	0.43	0.78
	condition		-0.43	-0.64 – -0.22	< 0.001	< 0.001
	cover × condition		0.05	-0.06 – 0.17	0.35	0.58
d. Amphibians						
threatened status	intercept	endemic	-0.33	-0.51 – -0.14	< 0.001	< 0.001
	cover		0.71	0.51 – 0.92	< 0.001	< 0.001
	condition		-0.74	-0.92 – -0.57	< 0.001	< 0.001
	cover × condition		0.10	-0.01 – 0.23	0.10	0.20
	intercept	non-endemic	-0.93	-1.15 – -0.70	< 0.001	< 0.001
	cover		0.74	0.56 – 0.93	< 0.001	< 0.001
	condition		-0.59	-0.75 – -0.44	< 0.001	< 0.001
	cover × condition		0.17	0.09 – 0.26	< 0.001	< 0.001
declining population	intercept	endemic	1.18	0.91 – 1.46	< 0.001	< 0.001
	cover		0.22	0.01 – 0.42	0.06	0.12
	condition		-0.99	-1.20 – -0.80	< 0.001	< 0.001
	cover × condition		-0.22	-0.33 – -0.08	< 0.001	< 0.001
	intercept	non-endemic	-0.09	-0.33 – 0.16	0.61	0.95
	cover		0.62	0.45 – 0.82	< 0.001	< 0.001
	condition		-0.76	-0.94 – -0.59	< 0.001	< 0.001
	cover × condition		0.18	0.08 – 0.29	< 0.001	< 0.001

Notes – A positive coefficient for the interaction term would suggest that the effect of forest structural condition on the response variable is stronger when small amounts of structurally intact forest remain within species humid tropical ranges, as opposed to when large extents are forested but structurally degraded. In contrast, a negative coefficient for the interaction term would indicate that the effect of forest structural condition on the response variable is stronger when large extents of structurally intact forest remain within species humid tropical ranges, as opposed to small fragments, irrespective of condition.

Supplementary Table 6. Sample sizes in terms of the number of rainforest endemic and non-endemic species included in analyses after excluding 2,751 and 2,155 species listed in IUCN criterion B for threatened status and declining population, respectively.

habitat	response variable	mammals	birds	reptiles	amphibians	total
endemic	threatened status	573	1,415	762	1,117	3,867
	declining population	372	1,362	283	950	2,967
non-endemic	threatened status	1,836	4,847	1,824	1,271	9,778
	declining population	1,182	4,500	1,050	999	7,731
total	threatened status	2,409	6,262	2,586	2,388	13,645
	declining population	1,554	5,862	1,333	1,949	10,698

Supplementary Table 7. Results of multiple phylogenetic logistic regression models contrasting the effects of forest cover, structural condition and structural integrity on the threatened status and declining population trend of humid tropical (a) mammals, (b) birds, (c) reptiles and (d) amphibians after excluding 2,751 and 2,155 species in IUCN criterion B for threatened status and declining population, respectively. Estimates represent median standardized coefficients (log odds) from 100 phylogenetic logistic regressions. The 95% confidence intervals of estimated coefficients were generated with 2,000 parametric bootstraps in each regression. Adj. *p*-value represents the False Discovery Rate (FDR)-adjusted *p*-value. We fit identical models separately for endemic and non-endemic species within each taxonomic group. Standardized coefficients generated by the models were exponentiated to obtain standardized odds ratios, and further converted to percentage odds using the formula $[e^{(\beta)} - 1] \times 100$ (Extended Data Fig. 2).

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
a. Mammals						
threatened status	intercept	endemic	-0.99	-1.52 – -0.49	0.01	0.01
	cover		0.29	0.00 – 0.60	0.14	0.18
	condition		0.01	-0.30 – 0.33	0.93	1.00
	integrity		-0.73	-1.00 – -0.50	< 0.001	< 0.001
	intercept	non-endemic	-1.90	-2.20 – -1.06	< 0.001	< 0.001
	cover		0.50	0.25 – 0.73	< 0.001	< 0.001
	condition		-0.22	-0.47 – 0.02	0.09	0.17
	integrity		-0.41	-0.61 – -0.21	< 0.001	< 0.001
declining population	intercept	endemic	0.95	0.40 – 1.50	< 0.001	< 0.001
	cover		-0.04	-0.54 – 0.48	0.83	1.00
	condition		-0.22	-0.72 – 0.25	0.43	0.63
	integrity		-0.35	-0.63 – -0.11	0.01	0.01
	intercept	non-endemic	0.07	-0.15 – 0.30	0.57	0.90
	cover		0.32	0.16 – 0.48	< 0.001	< 0.001
	condition		-0.33	-0.54 – -0.12	< 0.001	< 0.001
	integrity		-0.12	-0.26 – 0.02	0.12	0.24
b. Birds						
threatened status	intercept	endemic	-1.35	-1.59 – -1.08	< 0.001	< 0.001
	cover		0.22	-0.06 – 0.49	0.11	0.22
	condition		-0.43	-0.71 – -0.15	< 0.001	< 0.001
	integrity		-0.43	-0.61 – -0.25	< 0.001	< 0.001
	intercept	non-endemic	-2.55	-2.79 – -2.24	< 0.001	< 0.001
	cover		0.28	0.16 – 0.41	< 0.001	< 0.001
	condition		-0.20	-0.36 – -0.03	0.05	0.10
	integrity		-0.69	-0.87 – -0.52	< 0.001	< 0.001
declining population	intercept	endemic	1.04	0.81 – 1.28	< 0.001	< 0.001
	cover		-0.12	-0.39 – 0.14	0.35	0.67
	condition		-0.38	-0.64 – -0.12	0.01	0.01
	integrity		-0.05	-0.18 – 0.07	0.51	0.81
	intercept	non-endemic	-0.10	-0.18 – -0.01	0.02	0.04
	cover		0.11	0.01 – 0.20	0.02	0.03
	condition		-0.01	-0.15 – 0.13	0.23	0.45
	integrity		0.07	-0.02 – 0.16	< 0.001	< 0.001

Supplementary Table 7 (continued).

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
c. Reptiles						
threatened status	intercept	endemic	-1.79	-2.46 – -0.56	< 0.001	< 0.001
	cover		0.02	-0.30 – 0.34	0.94	1.00
	condition		0.06	-0.24 – 0.36	0.71	0.97
	integrity		-0.50	-0.82 – -0.18	< 0.001	< 0.001
	intercept	non-endemic	-2.68	-3.34 – -0.82	< 0.001	< 0.001
	cover		0.02	-0.18 – 0.22	0.91	1.00
	condition		0.08	-0.17 – 0.37	0.59	0.79
	integrity		-0.50	-0.91 – -0.11	< 0.001	< 0.001
declining population	intercept	endemic	-0.33	-0.91 – 0.24	0.33	0.49
	cover		0.30	-0.10 – 0.74	0.18	0.25
	condition		-0.61	-1.06 – -0.21	0.01	0.01
	integrity		-0.16	-0.45 – 0.13	0.24	0.37
	intercept	non-endemic	-2.06	-2.41 – -1.31	< 0.001	< 0.001
	cover		-0.16	-0.42 – 0.09	0.24	0.41
	condition		-0.07	-0.41 – 0.27	0.69	1.00
	integrity		-0.44	-0.76 – -0.15	0.01	0.01
d. Amphibians						
threatened status	intercept	endemic	-1.25	-1.75 – -0.85	< 0.001	< 0.001
	cover		0.34	0.11 – 0.61	0.02	0.03
	condition		0.20	-0.01 – 0.41	0.11	0.21
	integrity		-0.43	-0.60 – -0.28	< 0.001	< 0.001
	intercept	non-endemic	-1.81	-2.31 – -1.25	< 0.001	< 0.001
	cover		0.01	-0.14 – 0.16	0.92	1.00
	condition		0.17	-0.03 – 0.40	0.21	0.36
	integrity		-0.37	-0.62 – -0.15	< 0.001	< 0.001
declining population	intercept	endemic	0.28	-0.04 – 0.59	0.28	0.52
	cover		0.12	-0.12 – 0.36	0.39	0.65
	condition		-0.90	-1.18 – -0.63	< 0.001	< 0.001
	integrity		-0.26	-0.43 – -0.10	< 0.001	< 0.001
	intercept	non-endemic	-0.79	-1.09 – -0.47	< 0.001	< 0.001
	cover		0.08	-0.10 – 0.26	0.45	0.79
	condition		-0.30	-0.56 – -0.06	0.04	0.07
	integrity		-0.44	-0.66 – -0.23	< 0.001	< 0.001

Supplementary Table 8. Results of phylogenetic logistic regression models testing for interactions between forest cover and rainforest structural integrity on the threatened status and declining population trend of humid tropical (a) mammals, (b) birds, (c) reptiles and (d) amphibians after excluding 2,751 and 2,155 species in IUCN criterion B for Threatened status and Declining population, respectively. Estimates represent median standardized beta coefficients (log odds) from 100 phylogenetic logistic regressions. 95% confidence intervals of estimated coefficients were generated with 2,000 parametric bootstraps in each regression. Adj. *p*-value represents the False Discovery Rate (FDR)-adjusted *p*-value. We fit identical models separately for endemic and non-endemic species within each taxonomic group. See Extended Data Fig. 3 for predicted probabilities generated from these results.

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
a. Mammals						
threatened status	intercept	endemic	-1.04	-1.57 – -0.57	0.01	0.02
	cover		0.35	0.07 – 0.67	0.10	0.15
	integrity		-0.79	-1.20 – -0.40	< 0.001	< 0.001
	cover × integrity		0.06	-0.32 – 0.46	0.83	1.00
	intercept	non-endemic	-1.93	-2.25 – -1.44	< 0.001	< 0.001
	cover		0.45	0.23 – 0.66	< 0.001	< 0.001
	integrity		-0.55	-0.80 – -0.32	< 0.001	< 0.001
	cover × integrity		0.04	-0.22 – 0.30	0.52	0.98
declining population	intercept	endemic	0.90	0.33 – 1.47	< 0.001	< 0.001
	cover		-0.19	-0.58 – 0.21	0.41	0.60
	integrity		-0.52	-1.00 – -0.10	0.04	0.07
	cover × integrity		0.13	-0.27 – 0.58	0.57	0.86
	intercept	non-endemic	0.07	-0.16 – 0.31	0.57	0.94
	cover		0.25	0.12 – 0.39	< 0.001	< 0.001
	integrity		-0.29	-0.44 – -0.14	< 0.001	< 0.001
	cover × integrity		0.06	-0.09 – 0.21	0.56	1.00
b. Birds						
threatened status	intercept	endemic	-1.62	-1.97 – -1.32	< 0.001	< 0.001
	cover		0.16	-0.07 – 0.44	0.16	0.30
	integrity		-1.00	-1.40 – -0.66	< 0.001	< 0.001
	cover × integrity		0.43	0.14 – 0.77	0.01	0.01
	intercept	non-endemic	-2.68	-2.96 – -2.31	< 0.001	< 0.001
	cover		0.46	0.28 – 0.65	< 0.001	< 0.001
	integrity		-1.01	-1.25 – -0.79	< 0.001	< 0.001
	cover × integrity		0.34	0.14 – 0.55	< 0.001	< 0.001
declining population	intercept	endemic	1.18	0.96 – 1.42	< 0.001	< 0.001
	cover		-0.52	-0.70 – -0.33	< 0.001	< 0.001
	integrity		0.24	-0.01 – 0.49	0.07	0.14
	cover × integrity		-0.39	-0.60 – -0.18	< 0.001	< 0.001
	intercept	non-endemic	-0.12	-0.22 – -0.03	0.01	0.02
	cover		0.13	0.06 – 0.22	< 0.001	< 0.001
	integrity		0.07	-0.01 – 0.16	0.03	0.06
	cover × integrity		0.04	-0.04 – 0.12	0.24	0.47

Supplementary Table 8 (continued).

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
c. Reptiles						
threatened status	intercept	endemic	-2.58	-3.16 – -1.40	< 0.001	< 0.001
	cover		0.90	0.34 – 1.23	< 0.001	< 0.001
	integrity		-1.77	-2.26 – -0.79	< 0.001	< 0.001
	cover × integrity		1.23	0.46 – 1.62	< 0.001	< 0.001
	intercept	non-endemic	-2.98	-3.57 – -1.56	< 0.001	< 0.001
	cover		0.49	0.11 – 0.82	< 0.001	< 0.001
	integrity		-0.73	-1.17 – -0.20	< 0.001	< 0.001
	cover × integrity		0.51	0.06 – 0.91	0.01	0.01
declining population	intercept	endemic	0.44	-0.24 – 1.18	0.40	0.56
	cover		-0.61	-1.04 – -0.18	0.01	0.01
	integrity		0.34	-0.18 – 0.86	0.27	0.41
	cover × integrity		-0.80	-1.36 – -0.23	0.01	0.02
	intercept	non-endemic	-2.07	-2.46 – -1.27	< 0.001	< 0.001
	cover		-0.14	-0.43 – 0.16	0.40	0.60
	integrity		-0.48	-0.84 – -0.17	0.01	0.01
	cover × integrity		0.09	-0.30 – 0.50	0.58	0.80
d. Amphibians						
threatened status	intercept	endemic	-2.06	-2.47 – -1.48	< 0.001	< 0.001
	cover		1.23	0.80 – 1.56	< 0.001	< 0.001
	integrity		-1.44	-1.85 – -0.90	< 0.001	< 0.001
	cover × integrity		1.27	0.72 – 1.71	< 0.001	< 0.001
	intercept	non-endemic	-2.67	-3.18 – -2.19	< 0.001	< 0.001
	cover		0.44	0.09 – 0.81	0.03	0.04
	integrity		-0.66	-1.10 – -0.26	0.01	0.01
	cover × integrity		0.56	0.05 – 1.06	0.03	0.06
declining population	intercept	endemic	0.55	0.23 – 0.88	0.01	0.02
	cover		-0.31	-0.54 – -0.08	0.01	0.02
	integrity		-0.52	-0.78 – -0.25	< 0.001	< 0.001
	cover × integrity		-0.15	-0.47 – 0.15	0.35	0.66
	intercept	non-endemic	-0.77	-1.08 – -0.45	< 0.001	< 0.001
	cover		0.05	-0.13 – 0.25	0.57	0.89
	integrity		-0.63	-0.86 – -0.42	< 0.001	< 0.001
	cover × integrity		0.12	-0.14 – 0.40	0.35	0.56

Notes – A positive coefficient for the interaction term would suggest that the effect of forest integrity on the response variable is stronger when small amounts of high integrity (*i.e.,* structurally intact *and* low pressure) forest remain within species humid tropical ranges, as opposed to when large extents are forested but of low integrity. In contrast, a negative coefficient for the interaction term would indicate that the effect of forest integrity on the response variable is stronger when large extents of high integrity forest remain within species ranges, as opposed to small fragments, irrespective of integrity.

Supplementary Table 9. Results of phylogenetic logistic regression models testing for interactions between rainforest structural condition and integrity on the threatened status and declining population trend of humid tropical (a) mammals, (b) birds, (c) reptiles and (d) amphibians after excluding 2,751 and 2,155 species in IUCN criterion B for Threatened status and Declining population, respectively. Estimates represent median standardized beta coefficients (log odds) from 100 phylogenetic logistic regressions. 95% confidence intervals of estimated coefficients were generated with 2,000 parametric bootstraps in each regression. Adj. *p*-value represents the False Discovery Rate (FDR)-adjusted *p*-value. We fit identical models separately for endemic and non-endemic species within each taxonomic group. See Extended Data Fig. 4 for predicted probabilities generated from these results.

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
a. Mammals						
threatened status	intercept	endemic	-0.77	-1.31 – -0.29	0.08	0.14
	condition		0.08	-0.18 – 0.34	0.68	0.92
	integrity		-0.44	-0.83 – -0.10	0.05	0.08
	condition × integrity		-0.24	-0.53 – 0.03	0.11	0.19
	intercept	non-endemic	-2.04	-2.38 – -1.15	< 0.001	< 0.001
	condition		0.37	0.14 – 0.62	< 0.001	< 0.001
	integrity		-0.73	-1.06 – -0.40	< 0.001	< 0.001
	condition × integrity		0.13	-0.11 – 0.35	0.19	0.36
declining population	intercept	endemic	0.93	0.38 – 1.50	< 0.001	< 0.001
	condition		-0.23	-0.59 – 0.15	0.25	0.37
	integrity		-0.47	-0.95 – 0.01	0.06	0.10
	condition × integrity		0.08	-0.23 – 0.41	0.60	0.83
	intercept	non-endemic	0.10	-0.13 – 0.34	0.45	0.85
	condition		-0.12	-0.27 – 0.03	0.16	0.31
	integrity		-0.02	-0.21 – 0.17	0.38	0.74
	condition × integrity		-0.12	-0.26 – 0.02	0.10	0.20
b. Birds						
threatened status	intercept	endemic	-1.62	-1.94 – -1.29	< 0.001	< 0.001
	condition		-0.01	-0.25 – 0.25	0.77	1.00
	integrity		-0.91	-1.31 – -0.54	< 0.001	< 0.001
	condition × integrity		0.35	0.11 – 0.62	< 0.001	< 0.001
	intercept	non-endemic	-2.76	-3.06 – -2.41	< 0.001	< 0.001
	condition		0.25	0.05 – 0.44	0.01	0.01
	integrity		-1.00	-1.27 – -0.75	< 0.001	< 0.001
	condition × integrity		0.25	0.07 – 0.44	< 0.001	< 0.001
declining population	intercept	endemic	1.02	0.80 – 1.27	< 0.001	< 0.001
	condition		-0.47	-0.66 – -0.28	< 0.001	< 0.001
	integrity		0.02	-0.24 – 0.29	0.65	0.99
	condition × integrity		-0.04	-0.21 – 0.13	0.52	0.84
	intercept	non-endemic	-0.18	-0.28 – -0.08	< 0.001	< 0.001
	condition		0.27	0.16 – 0.38	< 0.001	< 0.001
	integrity		-0.33	-0.47 – -0.21	< 0.001	< 0.001
	condition × integrity		0.16	0.09 – 0.25	< 0.001	< 0.001

Supplementary Table 9 (continued).

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
c. Reptiles						
threatened status	intercept	endemic	-2.24	-2.88 – -1.13	< 0.001	< 0.001
	condition		0.38	0.07 – 0.70	0.02	0.03
	integrity		-1.08	-1.71 – -0.42	< 0.001	< 0.001
	condition × integrity		0.49	0.11 – 0.84	< 0.001	< 0.001
	intercept	non-endemic	-2.90	-3.63 – -1.27	< 0.001	< 0.001
	condition		0.11	-0.21 – 0.46	0.61	0.78
	integrity		-0.55	-1.12 – -0.13	0.02	0.04
	condition × integrity		-0.01	-0.45 – 0.42	0.75	0.99
declining population	intercept	endemic	-0.09	-0.71 – 0.48	0.74	1.00
	condition		-0.72	-1.13 – -0.36	< 0.001	< 0.001
	integrity		0.45	-0.10 – 0.99	0.16	0.24
	condition × integrity		-0.29	-0.67 – 0.07	0.15	0.23
	intercept	non-endemic	-2.06	-2.50 – -1.19	< 0.001	< 0.001
	condition		-0.18	-0.48 – 0.12	0.28	0.45
	integrity		-0.48	-0.89 – -0.11	0.02	0.02
	condition × integrity		0.14	-0.20 – 0.47	0.29	0.44
d. Amphibians						
threatened status	intercept	endemic	-1.22	-1.73 – -0.80	0.01	0.02
	condition		0.42	0.23 – 0.62	< 0.001	< 0.001
	integrity		-0.57	-0.87 – -0.31	< 0.001	< 0.001
	condition × integrity		0.17	-0.05 – 0.39	0.16	0.31
	intercept	non-endemic	-2.87	-3.42 – -2.40	< 0.001	< 0.001
	condition		0.47	0.09 – 0.88	0.02	0.04
	integrity		-0.82	-1.42 – -0.27	0.01	0.01
	condition × integrity		0.39	-0.08 – 0.83	0.10	0.17
declining population	intercept	endemic	0.41	0.08 – 0.74	0.13	0.26
	condition		-0.83	-1.06 – -0.62	< 0.001	< 0.001
	integrity		-0.15	-0.43 – 0.14	0.34	0.61
	condition × integrity		-0.12	-0.36 – 0.11	0.39	0.58
	intercept	non-endemic	-0.67	-0.99 – -0.37	< 0.001	< 0.001
	condition		-0.23	-0.44 – -0.01	0.07	0.12
	integrity		-0.39	-0.67 – -0.12	0.01	0.01
	condition × integrity		-0.20	-0.46 – 0.04	0.17	0.28

Notes – A positive coefficient for the interaction term would suggest that the effect of forest integrity on the response variable is stronger when small amounts of high integrity (*i.e.,* structurally intact *and* low pressure) forest remain within species humid tropical ranges, as opposed to when large extents are structurally intact but of low integrity (*i.e.* high human pressure). In contrast, a negative coefficient for the interaction term would indicate that the effect of forest condition on the response variable is stronger when large extents of high integrity forest remain within species humid tropical ranges, as opposed to small fragments, irrespective of integrity.

Supplementary Table 10. Results of phylogenetic logistic regression models testing for interactions between forest cover and forest structural condition on the threatened status and declining population trend of humid tropical (a) mammals, (b) birds, (c) reptiles and (d) amphibians after excluding 2,751 and 2,155 species in IUCN criterion B for Threatened status and Declining population, respectively. Estimates represent median standardized beta coefficients (log odds) from 100 phylogenetic logistic regressions. 95% confidence intervals of estimated coefficients were generated with 2,000 parametric bootstraps in each regression. Adj. *p*-value represents the False Discovery Rate (FDR)-adjusted *p*-value. We fit identical models separately for endemic and non-endemic species within each taxonomic group. See Extended Data Fig. 5 for predicted probabilities generated from these results.

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
a. Mammals						
threatened status	intercept	endemic	-0.94	-1.41 – -0.48	< 0.001	< 0.001
	cover		0.42	0.09 – 0.79	0.06	0.10
	condition		-0.66	-1.04 – -0.32	< 0.001	< 0.001
	cover × condition		0.01	-0.24 – 0.27	0.69	0.97
	intercept	non-endemic	-2.02	-2.37 – -1.04	< 0.001	< 0.001
	cover		0.63	0.34 – 0.91	< 0.001	< 0.001
	condition		-0.57	-0.81 – -0.31	< 0.001	< 0.001
	cover × condition		0.07	-0.05 – 0.17	0.19	0.36
declining population	intercept	endemic	0.99	0.44 – 1.54	< 0.001	< 0.001
	cover		0.13	-0.42 – 0.64	0.61	0.83
	condition		-0.75	-1.33 – -0.23	0.01	0.02
	cover × condition		0.08	-0.26 – 0.55	0.68	0.95
	intercept	non-endemic	0.11	-0.13 – 0.34	0.38	0.71
	cover		0.27	0.10 – 0.45	0.01	0.01
	condition		-0.40	-0.58 – -0.23	< 0.001	< 0.001
	cover × condition		-0.07	-0.15 – 0.02	0.11	0.21
b. Birds						
threatened status	intercept	endemic	-1.54	-1.77 – -1.29	< 0.001	< 0.001
	cover		0.31	-0.19 – 0.71	0.01	0.02
	condition		-0.77	-1.13 – -0.36	< 0.001	< 0.001
	cover × condition		0.05	-0.05 – 0.19	0.29	0.50
	intercept	non-endemic	-2.56	-2.81 – -2.09	< 0.001	< 0.001
	cover		0.59	0.39 – 0.76	< 0.001	< 0.001
	condition		-0.76	-0.93 – -0.57	< 0.001	< 0.001
	cover × condition		0.06	0.01 – 0.12	0.02	0.04
declining population	intercept	endemic	1.13	0.86 – 1.39	< 0.001	< 0.001
	cover		-0.16	-0.42 – 0.09	0.20	0.36
	condition		-0.33	-0.55 – -0.11	0.01	0.02
	cover × condition		-0.14	-0.21 – -0.07	< 0.001	< 0.001
	intercept	non-endemic	-0.15	-0.24 – -0.06	< 0.001	< 0.001
	cover		0.14	0.03 – 0.25	0.01	0.02
	condition		0.12	0.02 -0.22	0.02	0.04
	cover × condition		0.08	0.04 – 0.13	< 0.001	< 0.001

Supplementary Table 10 (continued).

response variable	predictor variables	habitat preference	estimate	95% C.I.	*p*-value	adj. *p*-value
c. Reptiles						
threatened status	intercept	endemic	-2.70	-3.28 – -2.16	< 0.001	< 0.001
	cover		0.41	-0.07 – 0.92	0.10	0.20
	condition		-0.55	-1.01 – -0.13	0.02	0.04
	cover × condition		0.40	0.18 – 0.37	< 0.001	< 0.001
	intercept	non-endemic	-2.78	-3.30 – -2.02	< 0.001	< 0.001
	cover		0.43	0.13 – 0.75	0.01	0.01
	condition		-0.31	-0.58 – -0.06	0.04	0.06
	cover × condition		0.09	-0.04 – 0.22	0.16	0.22
declining population	intercept	endemic	-0.37	-0.95 – 0.18	0.27	0.44
	cover		0.32	-0.09 – 0.78	0.18	0.27
	condition		-0.72	-1.17 – -0.33	< 0.001	< 0.001
	cover × condition		-0.01	-0.19 – 0.29	0.86	1.00
	intercept	non-endemic	-1.97	-2.32 – -1.12	< 0.001	< 0.001
	cover		-0.35	-0.66 – -0.06	0.03	0.05
	condition		-0.25	-0.56 – 0.07	0.13	0.21
	cover × condition		-0.16	-0.38 – 0.01	0.10	0.16
d. Amphibians						
threatened status	intercept	endemic	-1.34	-1.84 – -0.97	< 0.001	< 0.001
	cover		0.64	0.34 – 0.98	< 0.001	< 0.001
	condition		-0.37	-0.60 – -0.15	0.01	0.01
	cover × condition		0.10	-0.08 – 0.26	0.15	0.28
	intercept	non-endemic	-2.55	-3.28 – -1.89	< 0.001	< 0.001
	cover		0.13	-0.13 – 0.41	0.40	0.78
	condition		-0.02	-0.26 – 0.26	0.61	1.00
	cover × condition		0.11	-0.03 – 0.24	0.05	0.09
declining population	intercept	endemic	0.67	0.35 – 1.02	0.01	0.01
	cover		0.09	-0.17 – 0.34	0.53	0.90
	condition		-0.94	-1.20 – -0.68	< 0.001	< 0.001
	cover × condition		-0.45	-0.69 – -0.26	< 0.001	< 0.001
	intercept	non-endemic	-0.75	-1.08 – -0.40	< 0.001	< 0.001
	cover		0.09	-0.12 – 0.30	0.47	0.91
	condition		-0.55	-0.78 – -0.34	< 0.001	< 0.001
	cover × condition		-0.03	-0.15 – 0.09	0.63	0.99

Notes – A positive coefficient for the interaction term would suggest that the effect of forest structural condition on the response variable is stronger when small amounts of structurally intact forest remain within species humid tropical ranges, as opposed to when large extents are forested but structurally degraded. In contrast, a negative coefficient for the interaction term would indicate that the effect of forest structural condition on the response variable is stronger when large extents of structurally intact forest remain within species humid tropical ranges, as opposed to small fragments, irrespective of condition.

Supplementary Table 11. Phylogenetic signal parameter α measuring the strength of the phylogenetic correlation. When α = 1, evolution is approximately by Brownian motion on a given phylogeny and α > 1 indicates low phylogenetic correlations among species. α parameter estimates are provided for all additive and interaction models for all species.

habitat	response variable	α (95% CI)			
		mammals	**birds**	**reptiles**	**amphibians**
	response variable ~ forest cover + condition + integrity				
endemic	threatened status	0.02 (0.02 – 0.04)	0.37 (0.02 – 0.49)	0.03 (0.02 – 0.04)	0.01 (0.01 – 0.02)
	declining population	0.04 (0.02 – 0.08)	0.06 (0.05 – 0.08)	0.03 (0.02 – 0.04)	0.02 (0.01 – 0.03)
non-endemic	threatened status	0.08 (0.06 – 0.10)	0.05 (0.04 – 0.06)	0.05 (0.04 – 0.07)	0.02 (0.02 – 0.03)
	declining population	0.07 (0.06 – 0.09)	0.13 (0.11 – 0.14)	0.05 (0.03 – 0.06)	0.02 (0.02 – 0.03)
	response variable ~ forest cover × integrity				
endemic	threatened status	0.03 (0.02 – 0.04)	0.13 (0.05 – 0.19)	0.01 (0.01 – 0.02)	0.01 (0.01 – 0.02)
	declining population	0.04 (0.02 – 0.08)	0.06 (0.05 – 0.08)	0.02 (0.01 – 0.04)	0.03 (0.02 – 0.04)
non-endemic	threatened status	0.07 (0.06 – 0.09)	0.05 (0.04 – 0.06)	0.05 (0.04 – 0.06)	0.02 (0.02 – 0.03)
	declining population	0.07 (0.06 – 0.09)	0.14 (0.12 – 0.15)	0.04 (0.03 – 0.06)	0.02 (0.02 – 0.03)
	response variable ~ forest condition × integrity				
endemic	threatened status	0.03 (0.02 – 0.04)	0.39 (0.02 – 0.50)	0.03 (0.02 – 0.04)	0.01 (0.01 – 0.01)
	declining population	0.04 (0.01 – 0.08)	0.07 (0.05 – 0.09)	0.02 (0.01 – 0.03)	0.03 (0.02 – 0.04)
non-endemic	threatened status	0.06 (0.05 – 0.08)	0.04 (0.03 – 0.06)	0.05 (0.04 – 0.07)	0.02 (0.02 – 0.03)
	declining population	0.07 (0.05 – 0.08)	0.16 (0.14 – 0.18)	0.04 (0.03 – 0.05)	0.02 (0.02 – 0.03)
	response variable ~ forest cover × condition				
endemic	threatened status	0.05 (0.01 – 0.09)	0.44 (0.27 – 0.51)	0.04 (0.03 – 0.06)	0.03 (0.02 – 0.03)
	declining population	0.03 (0.01 – 0.04)	0.06 (0.05 – 0.08)	0.03 (0.02 – 0.04)	0.02 (0.01 – 0.02)
non-endemic	threatened status	0.10 (0.08 – 0.13)	0.14 (0.10 – 0.17)	0.06 (0.05 – 0.08)	0.02 (0.02 – 0.03)
	declining population	0.08 (0.06 – 0.09)	0.14 (0.12 – 0.15)	0.06 (0.04 – 0.07)	0.02 (0.02 – 0.02)

Supplementary Table 12. Phylogenetic signal parameter α measuring the strength of the phylogenetic correlation. When α = 1, evolution is approximately by Brownian motion on a given phylogeny and α > 1 indicates low phylogenetic correlations among species. α parameter estimates are provided for all additive and interaction models after excluding 2,751 and 2,155 species in IUCN criterion B for Threatened status and Declining population, respectively.

habitat	response variable	α (95% CI)			
		mammals	birds	reptiles	amphibians
response variable ~ forest cover + condition + integrity					
endemic	threatened status	0.02 (0.01 – 0.03)	0.06 (0.04 – 0.09)	0.01 (0.00 – 0.02)	0.01 (0.00 – 0.01)
	declining population	0.03 (0.02 – 0.05)	0.06 (0.05 – 0.08)	0.01 (0.01 – 0.03)	0.01 (0.01 – 0.02)
non-endemic	threatened status	0.06 (0.02 – 0.09)	0.05 (0.04 – 0.07)	0.01 (0.00 – 0.02)	0.01 (0.00 – 0.01)
	declining population	0.06 (0.05 – 0.08)	0.14 (0.12 – 0.16)	0.05 (0.01 – 0.08)	0.02 (0.01 – 0.03)
response variable ~ forest cover × integrity					
endemic	threatened status	0.02 (0.01 – 0.03)	0.06 (0.04 – 0.09)	0.01 (0.00 – 0.02)	0.01 (0.00 – 0.01)
	declining population	0.03 (0.02 – 0.05)	0.06 (0.05 – 0.08)	0.01 (0.00 – 0.02)	0.02 (0.01 – 0.02)
non-endemic	threatened status	0.06 (0.03 – 0.09)	0.05 (0.03 – 0.07)	0.01 (0.00 – 0.02)	0.02 (0.01 – 0.04)
	declining population	0.06 (0.05 – 0.08)	0.14 (0.12 – 0.16)	0.04 (0.01 – 0.08)	0.02 (0.01 – 0.03)
response variable ~ forest condition × integrity					
endemic	threatened status	0.02 (0.01 – 0.03)	0.07 (0.05 – 0.10)	0.01 (0.00 – 0.02)	0.01 (0.00 – 0.01)
	declining population	0.03 (0.01 – 0.05)	0.07 (0.06 – 0.09)	0.01 (0.00 – 0.02)	0.02 (0.01 – 0.02)
non-endemic	threatened status	0.07 (0.02 – 0.10)	0.05 (0.03 – 0.06)	0.01 (0.00 – 0.02)	0.02 (0.01 – 0.04)
	declining population	0.07 (0.05 – 0.08)	0.14 (0.12 – 0.15)	0.05 (0.01 – 0.08)	0.02 (0.01 – 0.02)
response variable ~ forest cover × condition					
endemic	threatened status	0.03 (0.02 – 0.05)	0.40 (0.23 – 0.49)	0.03 (0.01 – 0.08)	0.01 (0.01 – 0.01)
	declining population	0.04 (0.02 – 0.06)	0.06 (0.05 – 0.07)	0.02 (0.01 – 0.03)	0.01 (0.01 – 0.02)
non-endemic	threatened status	0.07 (0.02 – 0.10)	0.07 (0.04 – 0.09)	0.01 (0.01 – 0.02)	0.01 (0.01 – 0.04)
	declining population	0.06 (0.05 – 0.08)	0.14 (0.12 – 0.16)	0.05 (0.01 – 0.10)	0.02 (0.01 – 0.02)

Figures

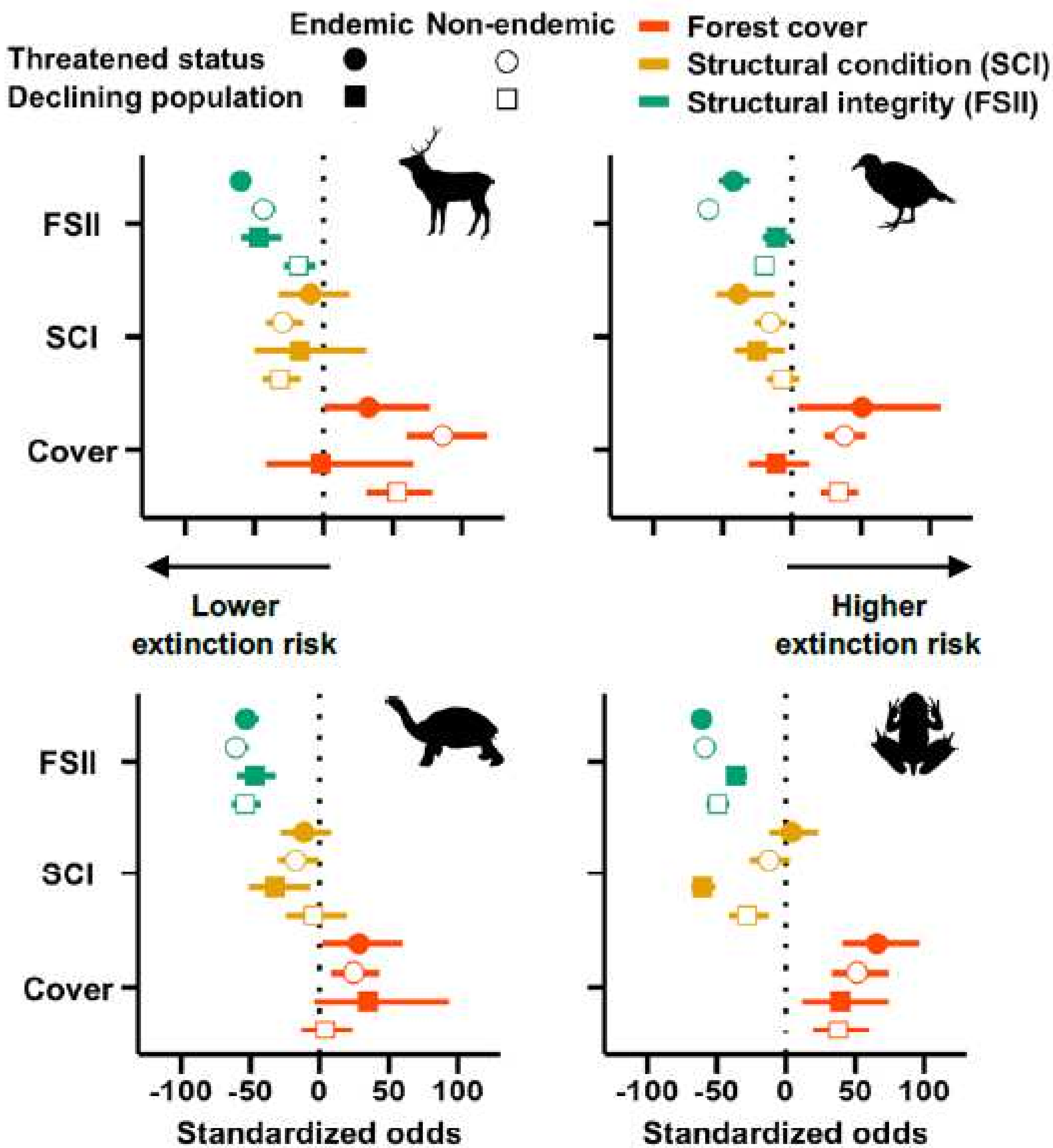


Figure 1

Effects of forest cover, structural condition and integrity on the threatened status and declining population trend of tropical rainforest mammals, birds, reptiles and amphibians. Point estimates represent median standardized odds of species being threatened (circles) or having a declining population (squares) generated by exponentiating standardized coefficients (log odds) of 100 phylogenetic logistic regressions to obtain standardized odds ratios, and thereafter converting to percentage odds to aid interpretation. Each regression was performed with one phylogenetic tree randomly drawn from 10,000 available trees for each taxonomic group, and separate models were parameterized for rainforest endemic and non-endemic species for each response variable. Error bars represent median 95% confidence intervals generated with 2,000 parametric bootstraps in each regression. See Supplementary Tables 1-2 for sample sizes and model results, respectively.

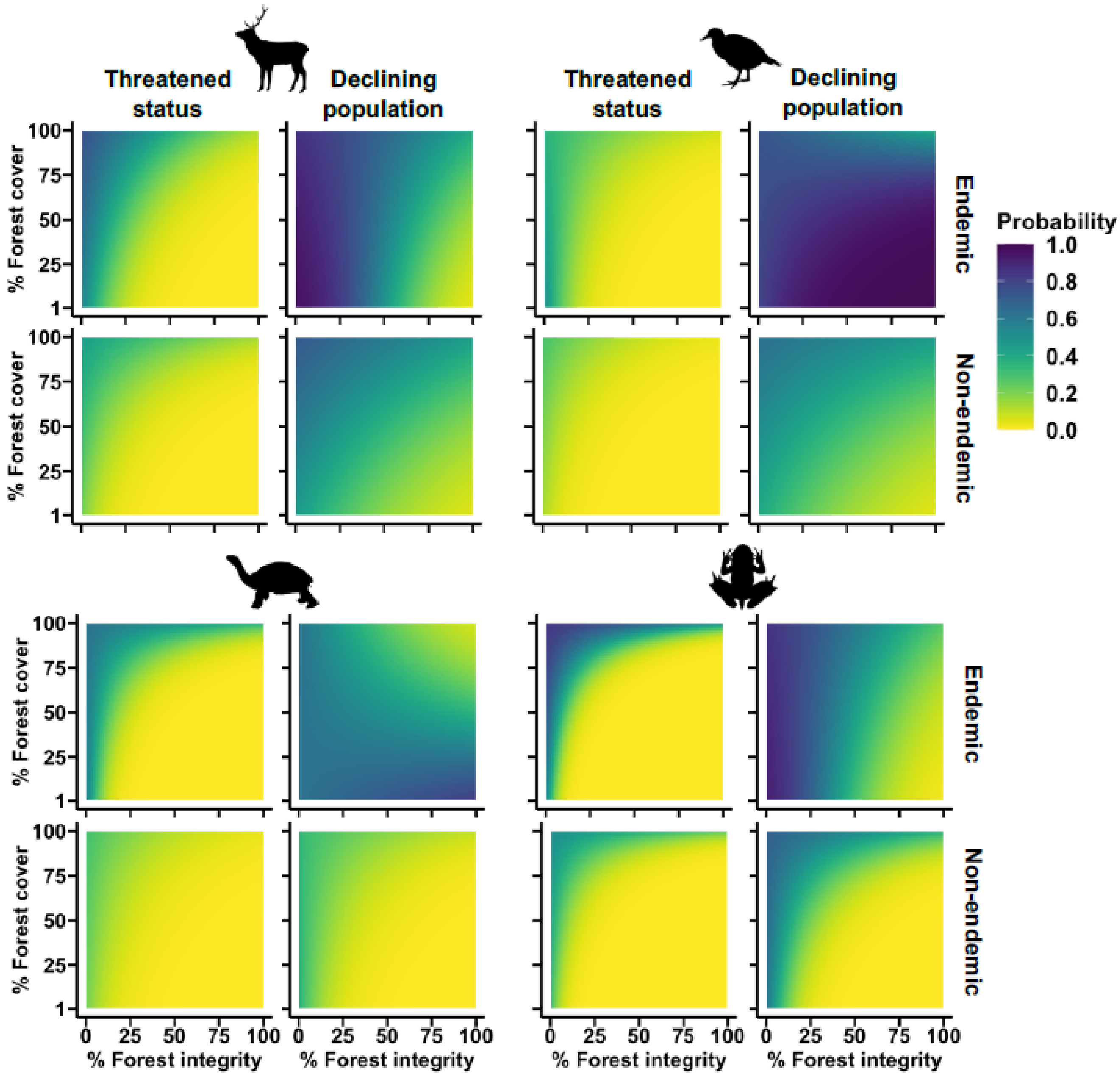


Figure 2

Predicted probabilities of mammals, birds, reptiles and amphibians being threatened or having declining populations as a function of forest cover area and the area of forests of varying integrity within species humid tropical ranges. Median predicted probabilities were generated from 100 phylogenetic logistic regressions. See Supplementary Tables 1 and 3 for sample sizes and model results, respectively.

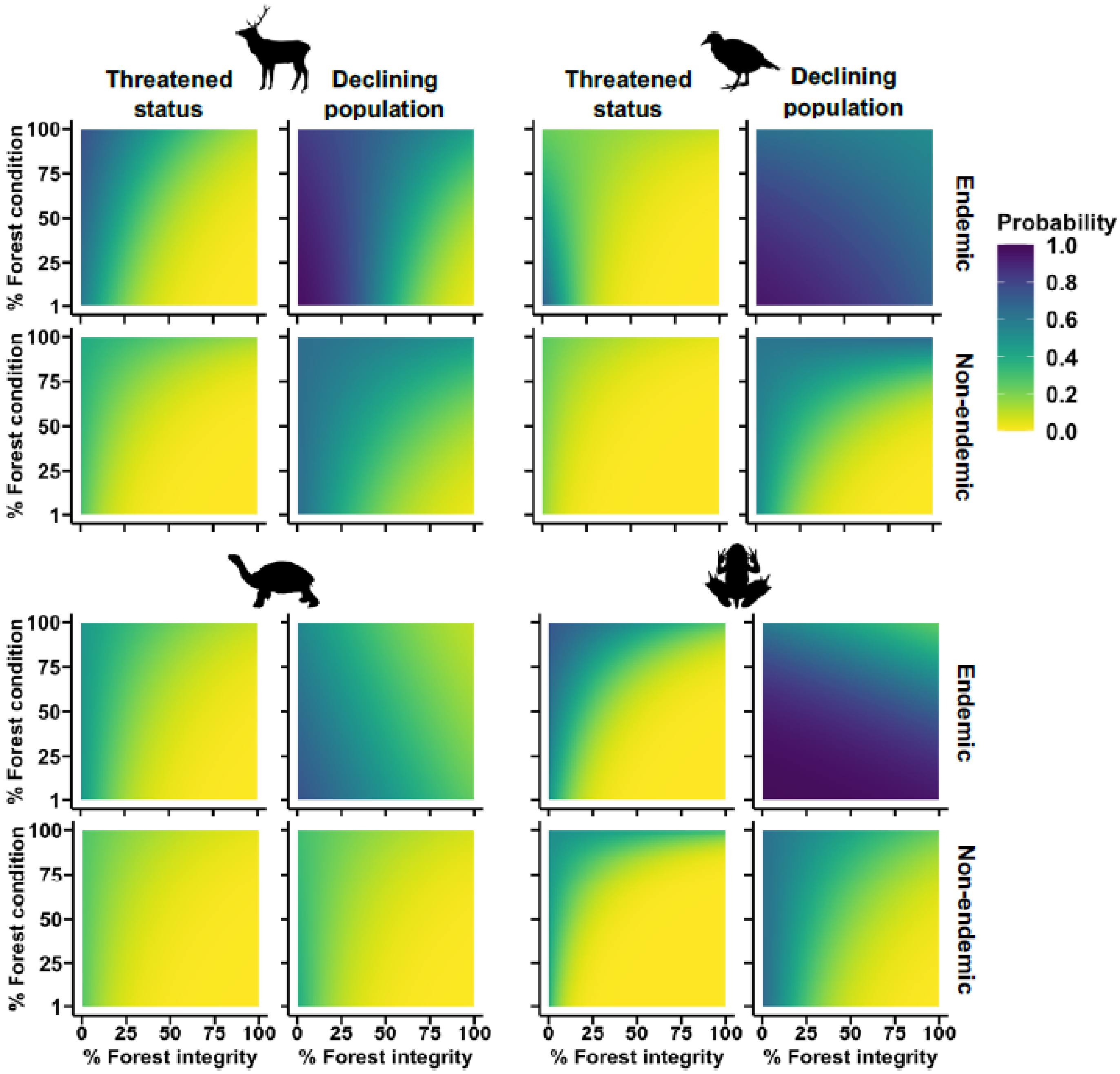


Figure 3

Predicted probabilities of mammals, birds, reptiles and amphibians being threatened or having declining populations as a function of the area under forests of varying condition and integrity within species humid tropical ranges. Median predicted probabilities were generated from 100 phylogenetic logistic regressions. See Supplementary Tables 1 and 4 for sample sizes and model results, respectively.