

Estimated Time to Act: A global assessment of biodiversity exposure to human modification

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Biodiversity loss is accelerating under compounding human pressures, yet most conservation tools quantify the pressure species already face, rather than when it will push them beyond the levels they have experienced. This temporal blind spot limits proactive planning, particularly under the Kunming-Montreal Global Biodiversity Framework (GBF), which sets action-oriented targets for 2030 and long-term goals for 2050. We link forecasts of cumulative human modification to 2040, which assume past patterns of change continue, to the area of habitat of 15,924 terrestrial mammal and bird species. Our framework adds species-specific exposure thresholds, aggregation across species or ranges, and an uncertainty envelope. We estimate exceedance under the mean HM forecast and under lower and upper trajectories that bound its 95% prediction interval, giving three estimates of exposure timing. We define the Estimated Time to Act (ETA) as the first year in which at least 30% of species in a local community exceed their exposure threshold. Based on the upper estimates, the community criterion is met on 19.7% of land by 2040, including 11.7% that the mean forecast alone does not flag, mostly land already moderately modified in 2015. On the same basis, almost a quarter of threatened species (24%) have at least half of their habitat exceeding their exposure threshold by 2040, more than twice the share of non-threatened species. Of 822 ecoregions, 338 combine moderate or high naturalness with high exceedance risk, most of them less than 30% protected. ETA complements existing biodiversity metrics by adding the dimensions of time and uncertainty. In doing so, it makes explicit the urgency implied by the GBF's deadlines, helping decision-makers identify where and when to act before pressure arrives.

Introduction

Biodiversity is declining globally under increasing human pressure (1), while the resources available to reverse these trends fall far short of what is needed (2, 3). Global and regional efforts to map human impacts and assess their consequences for biodiversity have advanced considerably, encompassing cumulative human modification time series (4), species-specific threat exposure (5, 6) and community-level intactness (7, 8). Together, these approaches show where those impacts are greatest and how much biodiversity has already changed. But for conservation action to be effective, we need to know not only the past changes and present state of biodiversity, but also its likely future trajectory. A parallel body of work projects biodiversity change under alternative socio-economic and emissions pathways to mid-

century and beyond (9). Such scenario-based projections have quantified potential habitat loss and extinction risk for individual species under future land-use change (10), estimated losses of local community diversity under both land-use and climate change (11), and shown that coordinated action could still reverse biodiversity declines (12). Within this broader effort, research on climate exposure has explicitly addressed when species and communities may encounter conditions beyond their historical experience. By deriving species-specific exposure limits from historically occupied climatic conditions and identifying the first year those limits are crossed, Trisos et al. (13) estimated the timing of exposure to unprecedented climate conditions across ecological communities. This approach has since been extended to quantify the share of each species' range exposed over time (14). While climate change is expected to become an increasingly important driver of biodiversity loss over coming decades, land-use change and other forms of direct human modification of ecosystems remain the largest causes of biodiversity decline in most regions today (15).

Extending this timing approach to cumulative anthropogenic pressure requires forecasts that capture where pressure may intensify. Human modification changes unevenly, with little change in most places and rapid increases in a few (16). Existing scenario-based projections often focus on a few drivers, mainly land-use and climate change, rather than the many direct pressures that co-occur in most places (17). Their estimates of biodiversity change often concern outcomes decades ahead and depend strongly on the model and scenario used (18). Near-term forecasts with quantified uncertainty align more closely with management timescales (19), as forecasts generally become less reliable the further ahead they look (20). While the timing of climate exposure has been estimated for species and communities, a comparable framework is needed to estimate when their exposure to cumulative anthropogenic pressure may exceed baseline conditions.

Acting before pressure intensifies retains more options (21), and vulnerability, encompassing both the timing and likelihood of loss, is a core consideration in systematic conservation planning (22). This need for timely action is reflected in the Kunming-Montreal Global Biodiversity Framework (GBF) (23), which sets deadlines for 2030 and 2050, but does not specify where action is most urgent. Several targets require spatial decisions within these deadlines: reducing the loss of areas of high biodiversity importance (Tar-

get 1), restoring at least 30% of degraded ecosystems (Target 2), effectively conserving at least 30% of land and inland waters (Target 3), halting human-induced extinction of known threatened species (Target 4), and integrating biodiversity values into planning and impact assessment (Target 14). With limited resources and little time left before 2030, anticipating where and when pressure may intensify can help identify where protection, restoration or other interventions are most time-critical. Yet the GBF's headline indicators largely track change that has already occurred (24–26), and therefore provide limited information on this emerging urgency.

To address this gap, we extend the timing approach of Trisos et al. (13) from climate to cumulative anthropogenic pressure. The resulting framework estimates when species communities, or individual species, may be exposed to pressure beyond their baseline conditions, turning a pressure forecast into an understanding of how conditions for biodiversity may change, and on what timeline. It rests on four components: (a) a forecast of cumulative pressure, (b) species-specific exposure thresholds, (c) aggregation of exceedance across species or across a species' range, and (d) an uncertainty envelope around the forecast. Here we apply it at 1 km resolution using the human modification index (HM) (4), which integrates multiple co-occurring pressures in one cumulative measure, and a forecast of HM to 2040 that assumes past patterns of change continue (16). Following Trisos et al. (13), we derive species-specific exposure thresholds from baseline conditions across each species' habitat and identify when forecast pressure exceeds those thresholds. Because each component can be replaced, the framework can be rebuilt with other pressure layers, taxa or forecasts, focused on subsets of species, ecosystems or conservation priorities of particular interest, and used from global to national and site scales.

The framework carries uncertainty in the pressure forecast through to estimates of exposure timing. We estimate exceedance under the mean HM forecast and under lower and upper trajectories that bound its 95% prediction interval (16), giving three estimates of exposure timing. Comparing these estimates identifies places where the upper 95% estimate lies above a species' baseline threshold even when the mean forecast does not. This distinction supports a precautionary interpretation: such places may warrant attention despite uncertainty about whether that exposure will occur, since uncertainty should not itself be a reason for inaction (27). We therefore foreground the upper estimates while reporting all three. Two features of the forecast justify this emphasis: its prediction intervals are well calibrated against data withheld from model training, and because change in HM is strongly right-skewed, the mean systematically underpredicts the large, rare increases that matter most for conservation (16). Reporting the mean alone would therefore understate precisely the outcomes that action is intended to avoid. Throughout, we report these bounds as upper estimates at each pixel, not as a joint scenario in which pressure reaches its upper bound everywhere at once.

Here we apply the framework globally to terrestrial mammals and birds. We ask where and when exposure to pressure above baseline levels could occur. We examine exposure in two complementary ways. At the community level, we map the first year in which a set share of species within a pixel exceeds their respective thresholds, calling it the Estimated Time to Act (ETA). At the species level, we estimate how much of each species' habitat is exposed, and when. Finally, as an example of use, we identify ecoregions that are not yet highly modified and have low protection coverage, but where exceedance risk under the upper trajectory is high.

Results

Global pressure landscape. We characterized the cumulative pressure to which species are exposed using historical time series and forecasts of global Human Modification (HM). HM increased consistently across the terrestrial surface from 1990 to 2020. A convLSTM model trained on these observed spatial and temporal dynamics (16) was used to forecast HM until 2040 in 5-year time steps. We used three forecast trajectories at each pixel to characterize its likely outcome as well as the plausible range of future pressures: a mean trajectory, and lower and upper trajectories corresponding to the 2.5th and 97.5th percentiles of the forecast, which bound a 95% prediction interval. We refer to results computed from these three trajectories as the lower, mean and upper estimates. Throughout, “trajectory” refers to a sequence of forecast values at a single pixel, not to a spatially coherent path followed by the landscape as a whole. Because the forecast bounds are estimated for each pixel separately, without modeling how nearby outcomes co-vary, they show the plausible range at each location rather than a joint scenario. The upper-bound map, for example, should not be read as a single future in which pressure is severe everywhere simultaneously. To relate these trajectories to current pressure levels and conservation or restoration potential, we classified each pixel by its 2015 HM value into one of three categories: low modified ($HM \leq 0.1$), moderately modified ($0.1 < HM \leq 0.4$), and highly modified ($HM > 0.4$) land. Globally, the majority of land in 2015 was under low human modification pressure (93.5 million km², 70.8% of land), with 21.3% (28.1 million km²) moderately modified and only 8.0% (10.5 million km²) highly modified (Table S1).

For each trajectory (mean, lower and upper) we summarized HM using spatial medians across all analyzed pixels within each class (low, moderate, high). Under the mean trajectory, global HM is forecast to increase by a median of +0.008 between 2015 and 2040, with the lower and upper trajectories bounding this at −0.010 and +0.080, respectively. This increase is concentrated in already-modified land: moderately modified pixels show a median increase of +0.044 (+20%) under the mean trajectory, ranging from −0.034 (−16%) under the lower trajectory to +0.185 (+86%) under the upper trajectory; highly modified pixels show a median increase of +0.055 (+11%) under the mean trajectory, ranging from −0.027 (−6%) under the lower trajectory to +0.203 (+41%) under the upper trajectory. Low-modified pixels show a neg-

ligible median increase of +0.005 under the mean trajectory, ranging from −0.004 under the lower trajectory to +0.049 under the upper trajectory (Fig. S1, Table S1).

Community-level exceedance. To understand how human modification pressure on terrestrial mammal and bird species is projected to change in the future in comparison to the level experienced in the past, we adapted the community-exposure framework of Trisos et al. (13). At each pixel, we calculated the proportion of species exceeding their species-specific exposure threshold, defined as the 95th percentile of each species' 2015 HM distribution across its area of habitat (AOH). The exceedance identifies exposure above the upper end of a species' baseline HM distribution and flags potentially heightened risk, but does not establish that its biological tolerance to pressure has been surpassed. We calculated these proportions for the years 2015 and 2020 with observed HM and for each modeled year through 2040 under the three HM trajectories (mean, lower, and upper). By 2040, communities exceeding their species-specific 2015 HM thresholds are found across all inhabited continents, with the extent and magnitude of community exceedance increasing from the lower HM forecast trajectory through the mean to the upper trajectory (Fig. 1). Higher proportions of species exceeding their thresholds broadly coincide with regions of established human pressure, particularly in eastern North America, Europe, South and East Asia, and parts of South America and Africa. These patterns are most spatially restricted under the lower trajectory and become progressively more extensive under the mean and upper trajectories.

We summarized this per-pixel exceedance proportion as its spatial median within each HM modification class, for each trajectory. Under the mean trajectory, the median proportion of species exceeding their threshold is forecast to remain at or below 0.01% in low-modified areas, and to increase from 0.08% to 1.94% (+1.86 percentage points, pp) in moderately modified areas between 2015 and 2040 (Fig. 1B). The largest increase under the mean trajectory occurs in highly modified regions, rising from a median of 10.53% to 53.51% (+42.98 pp), with hotspots evident across continents.

The lower and upper trajectories show the range of potential outcomes. Under the lower trajectory, changes by 2040 are comparatively modest: exceedance remains at or below 0.01% in low-modified areas and changes little in moderately modified areas (0.08% to 0.10%; +0.02 pp), with a more visible rise in highly modified areas (10.53% to 16.79%; +6.26 pp). Under the upper trajectory, by contrast, exceedance increases sharply across all classes: from 0.01% to 1.14% (+1.13 pp) in low-modified areas, from 0.08% to 25.35% (+25.27 pp) in moderately modified areas, and from 10.53% to 94.91% (+84.38 pp) in highly modified areas, approaching near-total exceedance across most highly modified land by 2040.

Estimated Time to Act: mapping global community urgency. For each pixel, we defined Estimated Time to Act (ETA) as the first assessed year in which the community exceedance criterion was met, i.e., at least 30% of the terrestrial

mammal and bird species exceeded their respective species-specific exposure thresholds, based on 2015 HM distributions (see Experimental Procedures and Fig. 1). We evaluated ETA under the lower, mean, and upper HM forecast trajectories. ETA translates species-level exposure into a temporal metric, distinguishing locations already meeting the community-level exceedance criterion from those projected to meet it before 2040, thereby informing the timing and spatial prioritization of conservation action. The 30% community exceedance criterion was selected a priori to identify exceedance shared across a substantial minority of the assessed community; it does not represent an empirically established threshold for ecological disruption.

The map of ETA (Fig. 2) shows where community exceedance risk is greatest under the upper bound of plausible future pressure (mean and lower trajectory in Fig. S2). By 2020, 5.3% of land had already met the 30% community exceedance criterion. Because each species' threshold is set at its own 95th percentile rather than its maximum HM value, up to 5% of any species' baseline habitat is expected to already sit above its own threshold by definition. The areas identified here are therefore places where species currently occur despite already facing among the highest cumulative pressure found anywhere in their range, raising concern for their ability to persist there in the long term, independent of any further increase in HM. Based on the upper estimates, 19.7% of land meets the criterion by 2040 (Table S3A), compared with 8.0% for the mean and 5.4% for the lower estimates. Most of this expansion occurs early: 13.4% of land is already in exceedance by 2030, closely tracking areas already under high pressure, before extending into a further 6.3% of land by 2040. This map is an indication where exceedance risk is greatest in the near to medium-term, and therefore most relevant to precautionary planning.

Across the full 2015–2040 period, 11.7% of land meets the criterion only in the upper estimates and not in the mean or lower estimates (Table S3B), representing community-level exposure that the mean forecast alone does not reveal. Most of this land was moderately modified in 2015 (61.8%), covering a third of all moderately modified land, with smaller shares in highly (21.0%) and low-modified land (17.2%; Table S3C). By contrast, the 2.7% of land newly meeting the criterion under the mean trajectory was almost entirely highly (50.7%) or moderately modified (43.8%). The rate of new exceedance grows through each successive forecast interval from 2025 to 2035, before dropping sharply by 2040. This pattern tracks the underlying HM trajectory: growth in HM stalls after 2035 in moderately and highly modified land, where most new exceedance originates, while HM continues to rise in low-modified areas over the same period (Fig. S1).

Species-level exceedance. Having established community-level exceedance through ETA, we next apply the same exceedance-threshold logic at the level of an individual species' range, to understand what proportion of each species' AOH lies above the 2015 exposure threshold, and by when. Because the forecast bounds are estimated independently at each pixel, this proportion is the share of

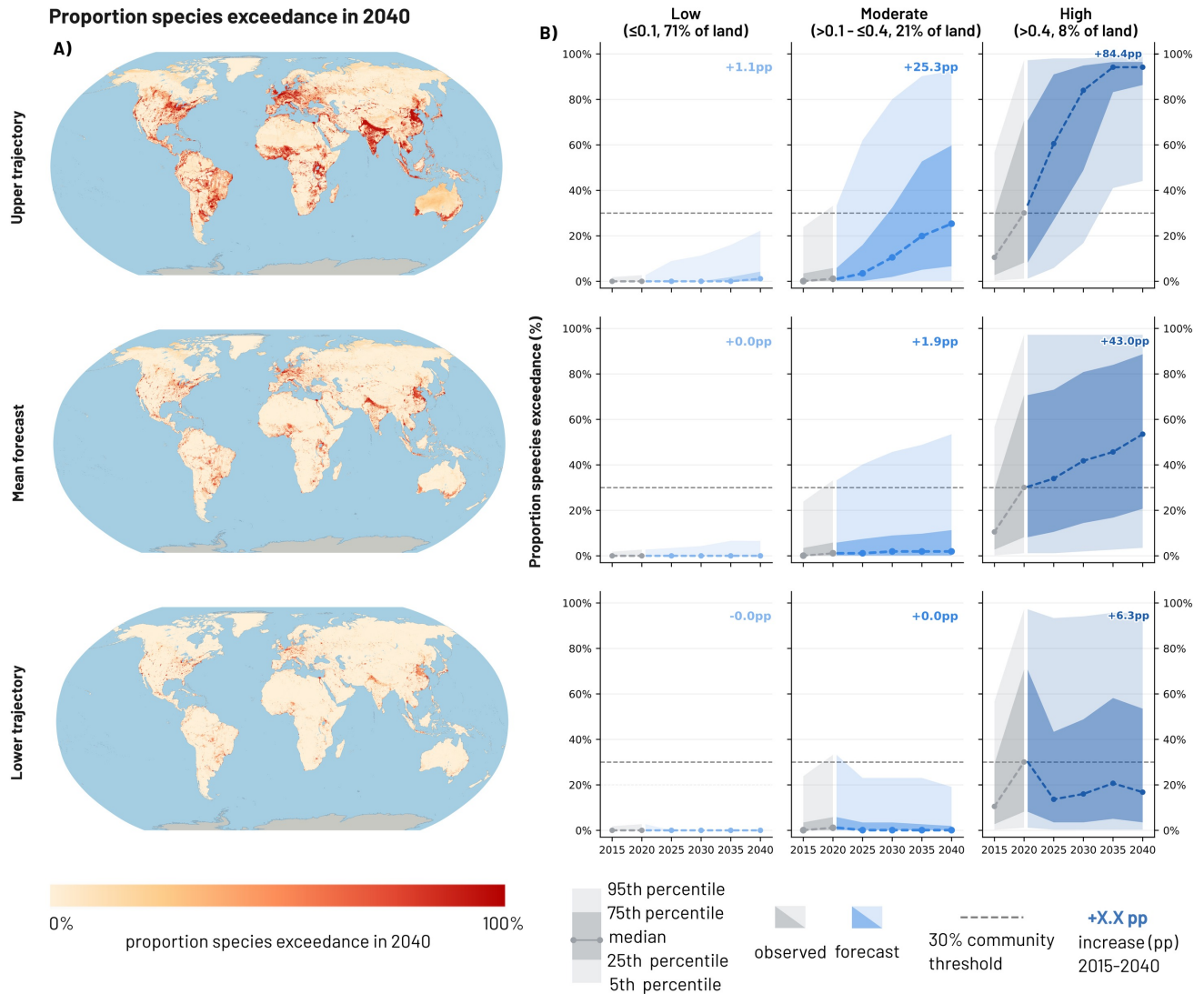


Fig. 1. Proportion of mammal and bird species exceeding their 2015 95th percentile HM threshold by 2040 across terrestrial areas. (A) Maps for the lower, mean and upper forecast trajectories. (B) Exceedance proportion over time by trajectory and 2015 HM class (low, $HM \leq 0.1$; moderately modified, $0.1 < HM \leq 0.4$; highly modified, $HM > 0.4$). Years with observed HM in gray, forecast years in blue; darker shading represents 25th–75th percentile; lighter shading, 5th–95th percentile. The dashed line through points connects the annual medians. The value in the top-right corner gives the change in the median from 2015 to 2040 in percentage points. The horizontal dashed line marks the 30% community exceedance criterion used to define ETA. Values for (B) are given in Table S2; the area of each HM class is given in Table S1.

1 km pixels within a species' AOH whose forecast HM is above that species' threshold; it is not an area that would be exceeded as a single, spatially coherent outcome. For each of the 15,924 species in the dataset, we calculated the cumulative proportion at each 5-year checkpoint from 2020 to 2040, under the lower, mean and upper HM forecast trajectories. The proportion is cumulative, so a pixel counts from the first year its HM is at or above the species' threshold, whether or not it remains above in later years. Species are grouped by IUCN Red List category (Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern, Data Deficient, and Unclassified, i.e., species that could not be matched to an IUCN Red List entry). We summarize exposure within each category as the median across its member species of the cumulative proportion of

AOH pixels exceeding their threshold at each year.

For threatened species, exceedance of the species-specific exposure threshold may warrant particular concern. Restricted ranges and small populations, characteristic of many threatened species, can increase vulnerability to additional pressures and stochastic events (28, 29). For some threatened species, especially those whose status is driven by pressures represented in HM, the 2015 HM exposure niche is likely to already include unfavorable conditions. Further exceedance could therefore add to existing pressures, making it particularly relevant when assessing conservation priorities.

Based on the upper estimates, species-level median cumulative exceedance by 2040 diverges substantially across IUCN categories, and ranges from 25.2% for Least Concern ($n = 11,384$) to 40.4% for Critically Endangered ($n = 318$)

Estimated Time to Act - Year to community exceedance (upper trajectory)

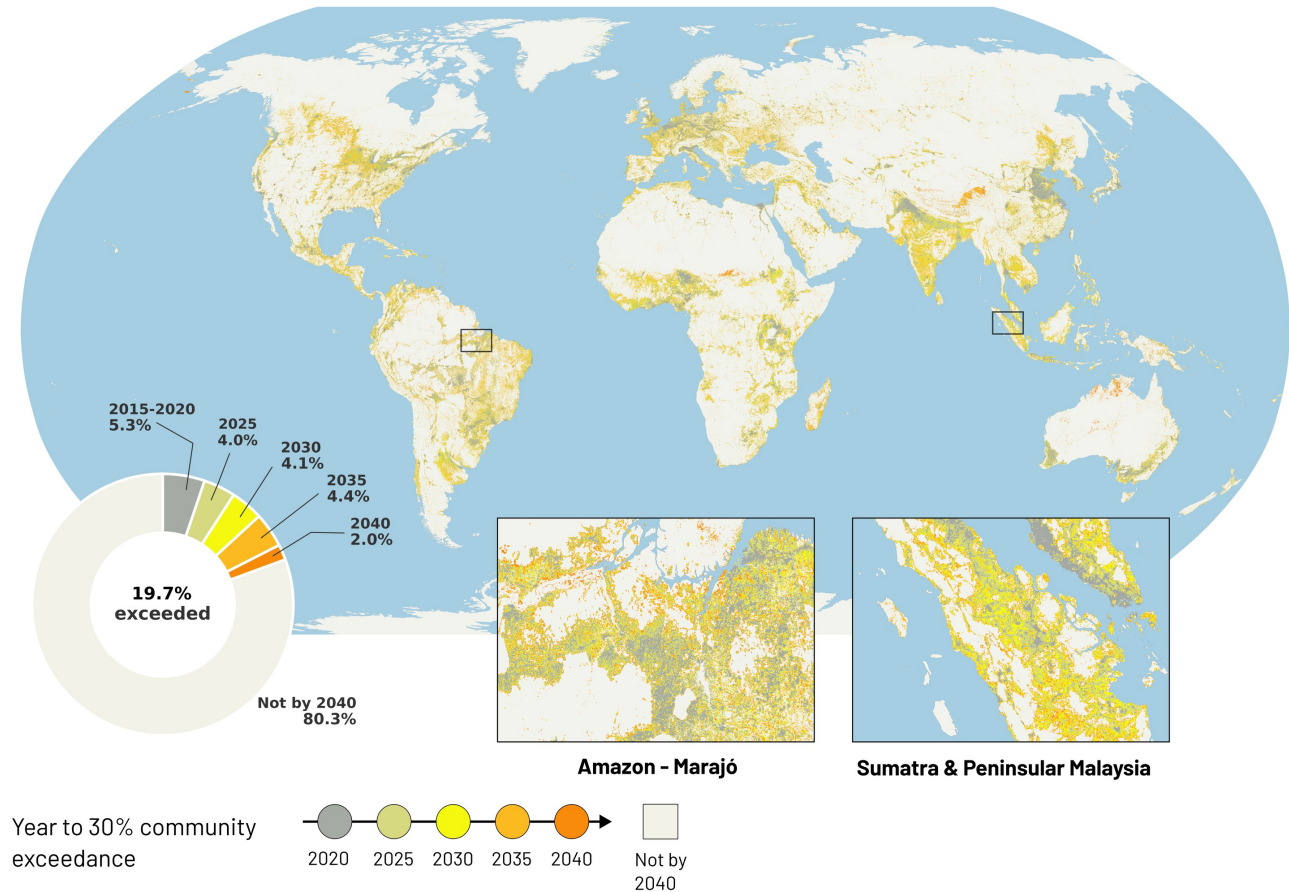


Fig. 2. Estimated Time to Act for the upper forecast trajectory. Dark gray are areas where at least 30% of mammal and bird species have exceeded their 2015 95th percentile HM value by 2020. Olive to orange areas exceed in the respective year from 2025 to 2040. Off-white are areas where the criterion is not met by 2040. Global map displaying the distribution of year to exceedance for the upper 97.5th percentile trajectory, with doughnut plot identifying the percent exceedance by year, and overall percent in center of plot. Segments may not sum to the total due to rounding. Zoom into ETA patterns in focal regions in the Amazon delta and in Sumatra and Peninsular Malaysia.

(Fig. 3, Table S4). This also tracks threat severity among the three threatened categories, with exceedance highest for Critically Endangered, followed by Endangered (35.1%, $n = 772$) and Vulnerable (31.8%, $n = 1,067$), underscoring the elevated risk facing the most threatened species. Data Deficient species ($n = 617$), which have been assessed but lack sufficient data for a threat category, show exceedance (32.7%) slightly above Vulnerable and Near Threatened (both 31.8%; $n = 1,067$ and $n = 1,210$) and slightly below Endangered (35.1%). Unclassified species (26.5%, $n = 556$) sit well below the threatened categories, though slightly above Least Concern. Based on the mean estimates, median cumulative exceedance by 2040 is low in all categories but follows the same order, from 8.5% (Least Concern) to 9.8% (Critically Endangered).

Based on the upper estimates, almost a quarter (24.2%) of threatened species have 50% or more of their habitat exceeding their exposure threshold by 2040, versus 11.2% of non-threatened species. At the 100% threshold, the gap widens further: 4.9% of threatened species have their entire habitat exceeding their threshold, compared with 1.5% of non-threatened species.

Species reaching 100% exceedance have disproportionately

small ranges and low variation in baseline HM in both groups. Among threatened species reaching full exceedance ($n = 105$), the median standard deviation of baseline HM is 0.0096 (vs 0.0852 for the remaining threatened species), and the median range is 147 km² (vs 11,222 km², about 76 times smaller). The same pattern holds among non-threatened species reaching full exceedance ($n = 203$): median standard deviation 0.0080 vs 0.0963, and median range 828 km² vs 286,416 km² (about 346 times smaller).

Data Deficient species show a heavy tail of exceedance. The median Data Deficient species has 32.7% of its habitat exceeding threshold by 2040, close to the 31.8% for Vulnerable and Near Threatened species, based on the upper estimates. However, 28.7% of Data Deficient species (177 of 617) have half or more of their habitat exceeding their threshold. This share is close to that of Critically Endangered species (35.8%) and about 1.5 times those of Vulnerable (18.7%) and Near Threatened species (19.5%). These 177 species are also narrowly distributed, with a median habitat area of 820 km² compared with 9,226 km² across Data Deficient species as a whole.

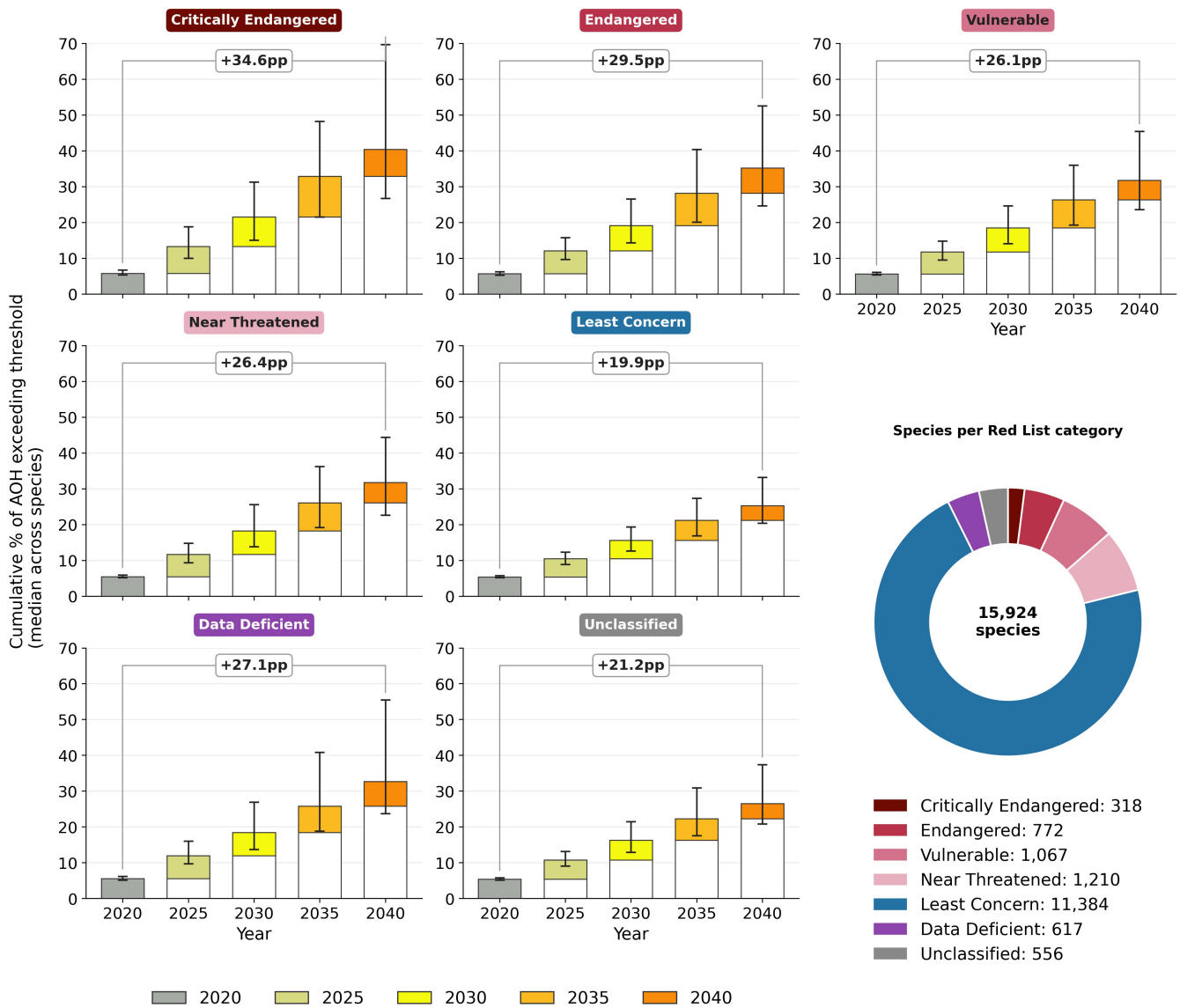


Fig. 3. Share of habitat exceeding the exposure threshold by IUCN category, based on the upper estimates. Each panel shows one category (Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern, Data Deficient) or Unclassified, i.e., species that could not be matched to the IUCN database. The donut chart shows the number of species in each category, with the number printed after each category label. Panel headings are color-coded to match it. Each bar top is the category's median cumulative percentage of AOH pixels exceeding their threshold in that year, taken across species at 5-year checkpoints from 2020 to 2040. The 2020 value of about 5–6% reflects the threshold definition, which is the 2015 baseline 95th percentile. The colored segment of each bar is the gap between that year's median and the previous year's median, and shows how much the median rose over the preceding 5-year period. The segment below is the median already reached at the previous checkpoint. Whiskers show the interquartile range of the cumulative percentage across species in that year, anchored at the bar top. The bracket above each panel gives the change in the median between 2020 and 2040, in percentage points. All panels share one y-axis (0–70%).

Ecoregion-level assessment: identifying where opportunity for new protection is greatest. To understand how community- and species-level exposure risk can inform relative conservation priorities across space and time, we assessed each RESOLVE ecoregion (30) on three dimensions: median proportional exceedance, the number of species at risk, defined as species with at least 20% of their in-ecoregion area of habitat above their threshold, and current naturalness (Human Modification, HM). We also calculated the proportion of each ecoregion already covered by protected areas and OECMs, using 30% coverage per ecoregion as a benchmark for ecologically representative protection, in line with the GBF's global 30×30 target.

Across the 822 ecoregions assessed, 421 (51.2%) retain high naturalness (mean $HM \leq 0.1$) as of 2020, and a further 354 (43.1%) fall into the moderate naturalness class ($0.1 < \text{mean } HM \leq 0.4$), leaving only 47 (5.7%) already substantially modified (mean $HM > 0.4$). Current naturalness and projected 2040 impact under the upper HM trajectory were negatively correlated across ecoregions (median per-pixel community exceedance: Spearman $\rho = -0.58$, $p = 9 \times 10^{-74}$; number of species at risk: $\rho = -0.62$, $p = 8 \times 10^{-88}$), consistent with projected HM increases, and the resulting exceedance, tending to occur more in land that is already moderately or highly modified rather than in currently low-modified areas. Against this general trend, a substantial

share of still-natural land carries high exceedance estimates for 2040. In 230 ecoregions (28.0%), moderate-or-high naturalness is combined with median community exceedance for 2040 in the highest third of all ecoregions, that is, in a typical pixel within these ecoregions, an unusually large share of the local species community is above its threshold. In 245 ecoregions (29.8%), moderate-or-high naturalness is combined with a top-tercile number of species for which at least 20% of their in-ecoregion range exceeds their threshold. In total, 338 ecoregions appear in at least one of the two sets, and 137 in both. The two impact metrics are themselves positively but only moderately correlated (Spearman $\rho = 0.61$), reflecting that they aggregate the same underlying exceedance layer over different axes. For both the median community-exceedance and species-at-risk upper classes, protection remains minimal: below 30% protected coverage for 201 of the 230 ecoregions flagged by median exceedance (87.4%) and 223 of the 245 ecoregions flagged by species at risk (91.0%), with a median protected coverage of just 7.2% and 6.7% respectively.

Under the median community-exceedance lens, Neotropic ecoregions lead (41.4%), followed by Australasia (37.3%), Indomalayan (32.1%), Afrotropic (27.0%), Nearctic (20.9%), and Palearctic (18.0%). The most extreme cases by this metric (naturalness ≥ 0.9 , top tercile on median exceedance) are dominated by Australasia (19 of 43), led by Madagascar humid forests, the Tibetan Plateau alpine shrublands and meadows, and several Australian arid- and savanna-biome ecoregions alongside Wrangel Island Arctic desert. In each, a typical pixel carries an unusually high share of its resident community past threshold by 2040. These are sparse, low-richness communities in which a small absolute number of species at risk represents a disproportionately large share of the community.

Under the species-at-risk lens, the realm pattern shifts: Neotropic ecoregions are now even more disproportionately represented, with a higher share of Neotropic ecoregions meeting the joint condition of moderate-or-high naturalness and top-tercile species at risk: 56.9% of all Neotropic ecoregions qualify, followed by Indomalayan (51.9%) and Afrotropic (46.1%). By contrast, Palearctic, Australasian, and Nearctic ecoregions are markedly less often flagged as meeting this joint condition, at $\leq 12.2\%$ each. Australasia in particular falls from second-most-represented realm (37.3%) under the community-exceedance lens to just 9.6% for species-at-risk. This concentration sharpens further at the extreme: among ecoregions at naturalness ≥ 0.9 specifically, 39 of the 60 in the top species-at-risk tercile are Neotropic, concentrated in the Andean-Amazon transition of Colombia, Ecuador, and Peru: the Magdalena Valley montane forests (1,020 species with at least 20% of their in-ecoregion range exceeding their threshold by 2040, 28.1% protected), Eastern Cordillera Real montane forests (1,019 species, 23.3% protected), Ucayali moist forests (953 species, 21.7% protected), and Cordillera Oriental montane forests (887 species, the best-protected of this group at 48.9%), alongside Central Zambesian wet miombo woodlands in Central Africa (740

species, 14.9% protected) as the principal non-Neotropic exception. This pattern is distinct from, rather than competing with, the community-exceedance metric's emphasis on sparse, low-richness realms like Australasia.

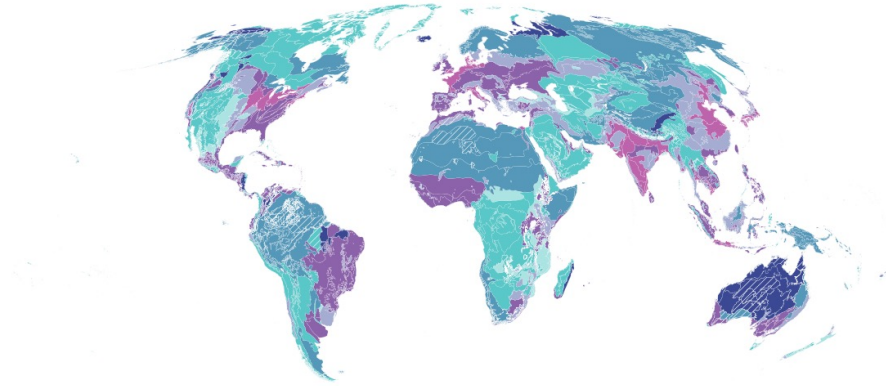
A geographically distinct pattern emerges among already-modified ecoregions: of the 44 low-naturalness ecoregions in the top tercile for median community exceedance, 19 (43.2%) are Indomalayan, as are 19 of the 29 (65.5%) in the top tercile for species at risk, compared with only 3 and 1 Neotropic ecoregions, respectively, suggesting that legacy land conversion combined with continuing exposure risk is concentrated in South and Southeast Asia. Protection levels do not track exposure evenly across realms or lenses. Among the ecoregions flagged by median exceedance, Neotropic ecoregions have the highest median protection (9.4%), and Afrotropic (4.3%) and Nearctic (4.8%) the lowest. Among those flagged by species at risk, Neotropic is again highest (12.2%), with Indomalayan (3.9%) and Nearctic (3.5%) lowest. Across realms these medians span 3.5% to 12.2%, so no realm comes close to the 30% benchmark, and the Nearctic is among the least protected under both lenses.

Discussion

By extending the timing approach developed for climate exposure (13, 14) to cumulative human pressure, we find that human modification and the associated exposure of species to threats intensify across the terrestrial surface through 2040. The community exceedance criterion (at least 30% of species in a 1 km pixel beyond their exposure threshold) is met on 8.0% of land by 2040 based on the mean forecast, and on 19.7% (26.1 million km²) based on the upper estimates. On 11.7% of land, the criterion is met only in the upper estimates, revealing risk that the mean forecast alone does not show. This pattern is not uniform in space. Under the mean forecast, only 2.7% of land newly meets the criterion between 2020 and 2040, and almost all of it was already moderately (44%) or highly modified (51%) in 2015 (Table S3C). The upper estimates place exceedance far more widely. Most of the land where the criterion is met only under this trajectory is moderately modified (62%), covering a third of all such land, with smaller shares of highly (21%) and low-modified land (17%). The pattern also differs across species. Based on the mean forecast, the median share of habitat exceeding its threshold by 2040 is low in all Red List categories, but already increases with threat status, from 8.5% for Least Concern to 9.8% for Critically Endangered species. In the upper estimates, this gradient widens to 25.2% and 40.4%. Together, the timing of community exposure and the share of each species' habitat exceeding their threshold show where and when action may be most needed, and the comparison between trajectories shows how certain that exposure is. Community- and species-level exceedance are complementary, and the ecoregion example combines both (Fig. 4).

Looking beyond the most likely outcome. Comparing exceedance under the mean and upper trajectories, rather than relying on the mean forecast alone, shows how confident we

A) Median exceedance proportion 2040



B) Nr species $\geq 20\%$ of in-ecoregion range exceeded 2040

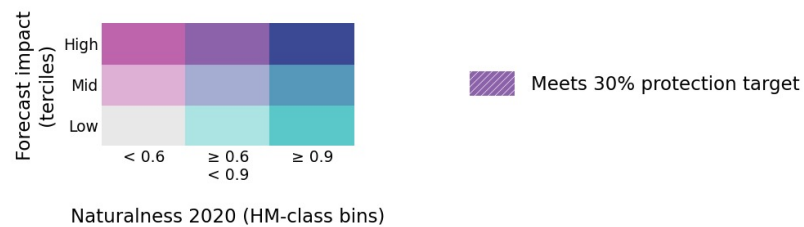
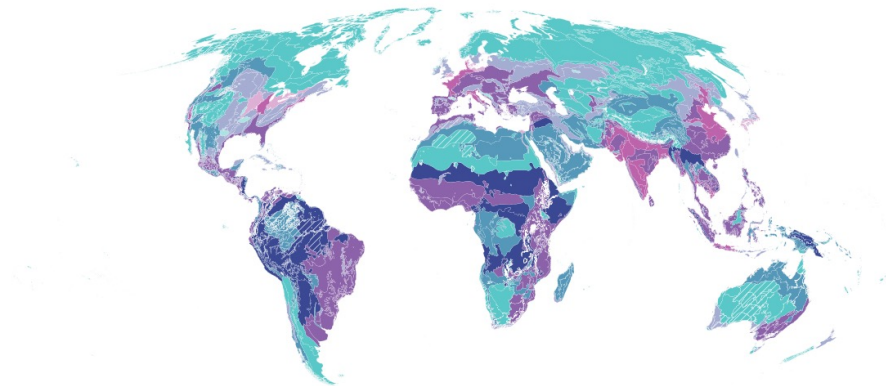


Fig. 4. Ecoregion naturalness against species and community exceedance. Each ecoregion polygon is colored by a 3×3 bivariate classification combining current naturalness (2020; $1 - \text{HM}$, x-axis) with one impact metric (y-axis), under the upper HM forecast trajectory for 2040. Naturalness is grouped into three classes using fixed inverted Human Modification cut-offs (low naturalness, $\text{HM} > 0.4$; moderate, $0.1 < \text{HM} \leq 0.4$; high, $\text{HM} \leq 0.1$). (A) Impact is the median per-pixel proportion of the local species community exceeding its threshold. (B) Impact is the number of species with $\geq 20\%$ of their in-ecoregion area of habitat exceeding their 2015 95th-percentile HM threshold by 2040. Species are counted by the exceedance of their habitat within each ecoregion, irrespective of the share of their total range that lies there. In both panels, impact is split into equal-count terciles (bottom/middle/top third). The resulting nine classes use a blue–purple bivariate palette (low/high indicated on the legend). The top-right (dark navy) class marks ecoregions in the high-naturalness bin and the top impact tercile: still largely intact, but facing the most severe forecast species or community exceedance. The top-left (magenta) class is low-naturalness with high projected impact; the bottom-right (teal) is high-naturalness with low projected impact; bottom-left (light gray) is low on both. Hatching marks ecoregions where protected areas and OECMs already cover at least 30% of the ecoregion's area. The two panels share the same x-axis variable and bin edges, and the same palette, differing only in which impact metric defines the y-axis and its terciles.

can be in a projected outcome as well as where and when it occurs. On 2.6% of land, both trajectories indicate that the criterion is met between 2025 and 2040 (Table S3B). Here, confidence in near-term exposure is higher, and the case for action rests on a robust projection. On a further 11.7% of land, only the upper trajectory indicates exceedance. The outcome is less certain, but it marks exposure that a best-guess forecast would not reveal. This shifts the rationale for action from prediction to precaution (27), particularly where the consequences of delayed action would be difficult to reverse. Most of this land is moderately modified (Table S3C). There, the median share of species beyond their exposure threshold rises by 2 percentage points by 2040 under the mean forecast, but by 25 points under the upper trajectory. The divergence arises because change in HM is strongly right-skewed: most land changes little, while a small share changes a lot. The mean forecast underpredicts these large, rare increases, which often occur with little preceding signal (16). Moderately modified land is also where human modification has expanded most in the past. Between 1990 and 2020, HM increased on 24% of terrestrial land (31 million km²), and 45% of that area was moderately modified in 1990 (4). The upper trajectory bounds a 95% prediction interval and is estimated independently at each pixel. It therefore describes an envelope of plausible exposure at each location, not a single future in which pressure rises everywhere at once.

Exposure of threatened species. Based on the upper estimates, the share of habitat exceeding the exposure threshold by 2040 rises with IUCN threat status. For the typical (median) species, the share of habitat exceeding its threshold by 2040 increases from 25.2% for Least Concern to 40.4% for Critically Endangered species. In total, 24.2% of threatened species have half or more of their habitat exceeding their threshold, more than twice the share of non-threatened species (11.2%). This gradient is consistent with expert assessments of extinction risk, even though exceedance is derived only from forecast pressure and species' habitat, with no reference to Red List status. Range size accounts for part of this agreement, since it is the trait most consistently associated with extinction risk (28) and is smaller among threatened species in our data (Table S4). Small ranges also tend to carry narrow and low baseline HM distributions. This sets a low threshold, so even modest increases in pressure place a large share of habitat above it. The same narrow baseline also describes a species whose habitat lies almost entirely at low levels of human modification. Such species may depend on specialized conditions, and they have little habitat below threshold to fall back on. Data Deficient species have been assessed, but lack the information needed to estimate their extinction risk. They show the same pattern as reported above, with a share of species past the halfway mark close to that of Critically Endangered species, and similarly small ranges. As a group, Data Deficient species may be more threatened than species with a threat category. Borgelt et al. (31) used machine learning to predict that more than half of Data Deficient species are threatened. For these species, high exceedance is a flag for reassessment and targeted data collection. Sites har-

boring range-restricted and threatened species have also been proposed as near-term priorities for protection (32).

Implications for conservation planning. ETA has different implications depending on the baseline condition of the land and on the conservation strategy considered. Low-modified land makes up 17% of the area where the community exceedance criterion is met only under the upper trajectory (Table S3C). In these places, protection, stewardship or land-use planning could avoid loss before pressure arrives. The benefit of protection depends on what would otherwise happen: it is greatest where pressure would intensify in its absence, and smallest where land is unlikely to change. Protected areas have historically been concentrated on land that is remote, steep or otherwise unattractive for production (33), and have often been poorly aligned with where they would make the most difference (34). Anticipating when pressure is likely to reach a place is one input to that judgment, and is what ETA is intended to provide.

Moderately modified land is where the trajectories diverge most. It accounts for 44% of the land newly meeting the community exceedance criterion under the mean forecast, and for 62% of the land meeting it only under the upper trajectory, a third of all moderately modified land (Table S3C). Kennedy et al. (35) proposed such land as a timely conservation priority, where proactive planning can maintain biodiversity before land becomes human-dominated. Here, protection of remaining natural areas, restoration and improved management are likely to be needed together. In highly modified land, exposure is largely already present. Restoration and management therefore become more relevant than avoided loss, and the forecast can show where pressure is expected to stabilize (16). These strategies complement each other. New protected areas increasingly require restoration, restored areas require protection to secure their gains, and the value of both depends on the surrounding landscape.

The ecoregion assessment shows how ETA can be combined with information on current condition and protection. Its two lenses highlight different places. Community exceedance is a share of the species present, so it is somewhat agnostic to whether areas are species-rich and species-poor. It therefore picks out sparse communities, for example in Australasia, including central Australia. The number of exposed species instead highlights species-rich regions, such as the Andean–Amazon transition. Of the 274 ecoregions in the highest third for median community exceedance, 230 retain moderate or high naturalness, as do 245 of the 274 highest for species at risk, based on the upper estimates. Of these, 87% and 91% are less than 30% protected, with a median protected-area coverage of 7.2% and 6.7%. Under GBF Targets 1–3, such assessments can help identify where spatial planning, restoration and new area-based conservation could anticipate exposure, rather than respond to it once it has occurred.

ETA is one input into conservation planning. It indicates where new protection or other interventions may be most urgent. It does not assess whether the existing protected-area network is adequate (36) or effectively managed (37). Decisions about where to act should combine this signal with

information on feasibility, cost, governance capacity, and local ecological and social context. They should also consider commitments to ecological representativeness, connectivity and areas of importance for biodiversity (38).

ETA among biodiversity indicators. ETA is designed to complement existing biodiversity indicators. It adds a broader, multi-threat pressure signal and a forward-looking, temporal dimension with uncertainty bounds. Knowing that an area is in poor or good condition today does not show whether that condition is stable or likely to come under new pressure before 2040. Several indicators used under the GBF describe the current or past state of biodiversity. The Species Habitat Index (SHI) measures change in the extent and connectivity of suitable habitat relative to a fixed baseline (39), and the Biodiversity Intactness Index (BII) estimates how much of the original community abundance remains (8, 40). The Living Planet Index tracks trends in monitored vertebrate populations (41). These indicators describe how much has already changed, and SHI and BII are driven mainly by land cover and land use. ETA instead estimates when future pressure could move a local community beyond its baseline exposure, using cumulative human modification, which combines stressors mapped to IUCN threat classes.

ETA also differs from species-focused risk indicators. The Red List Index (RLI) tracks the average extinction risk of species groups over time, based on changes between Red List categories, and is usually reported as a global or national trend (42). STAR quantifies how much abating threats and restoring habitat in specific places could reduce species' extinction risk, based on the threats recorded in Red List assessments (6). Both the species Red List and the Red List of Ecosystems, a GBF headline indicator, allow projected declines to be used in assessments (29, 43), but projections of future pressure are not routinely available. ETA operates instead at the level of the local co-occurring community and of species ranges, and remains spatially explicit. Rather than summarizing overall risk as a single trend, it distinguishes where and when exposure could arise, which is the information most directly relevant to prioritizing new conservation action. Its outputs could therefore also inform future-decline criteria and other indicators. Because ETA is calculated separately under the lower, mean and upper forecasts, it is reported as three maps rather than one (Fig. 2 and Fig. S2), and the differences between them show how much the timing of exposure depends on which forecast is realized. The 11.7% of land that meets the criterion only in the upper estimates is one example, with an ETA inside the forecast window based on the upper estimates and none based on the mean.

Interpreting exposure. ETA signals exposure to unusually high pressure relative to a species' baseline; it does not establish ecological harm or the crossing of a biological tolerance threshold. Because HM is a cumulative, multi-dimensional index, a given exceedance value may reflect different underlying pressures for different species. Thresholds are derived from the 95th percentile of each species' 2015 baseline HM distribution, so exceedance is measured relative to conditions

the species was already experiencing, not relative to a level known to be safe. For threatened species, that baseline may already include unfavorable conditions. The threshold also depends on the pressure present within a species' range. A low threshold may therefore reflect a lack of highly modified land within the range rather than sensitivity to pressure. Limits estimated from where species occur, and do not occur, along a gradient of human pressure reduce this dependence, as shown for bird species using occurrence records (44). Comparable data are not yet available for most species, but such limits could refine species thresholds where they exist.

Low HM exposure does not indicate an absence of pressure. Threats such as hunting, invasive species and disease are not directly captured by cumulative human modification, although HM partly reflects the access and disturbance that enable them, through human accessibility, roads and settlements. Hunting and trapping is the most geographically widespread threat to mammals and birds, and maps of human pressure that exclude it underestimate the overall pressure on biodiversity, particularly in areas of the highest biodiversity importance (45). Hunting also adds to the effects of land use on tropical mammals (46) and ETA is therefore likely to underestimate exposure where hunting dominates, particularly in tropical forests.

Exceedance is computed from two datasets, species habitat and forecast human modification, and each carries its own limitations. First, the Area of Habitat (AOH) maps combine each species' geographic range, typically drawn from point localities and expert knowledge rather than a fully model-based distribution, with expert-informed habitat associations and 2015 land cover (47). Both the range and the habitat refinement therefore carry expert-informed uncertainty. How far a species' range reflects systematic modeling rather than expert-drawn boundaries varies considerably across the dataset: well-studied species benefit from more detailed distribution modeling, while for many others the range is closer to an expert-informed approximation. In both cases, the mapped range depends on the underlying occurrence records, and neither shows exactly where a species occurs. ETA accordingly reflects inferred rather than confirmed exposure. Even so, AOH remains among the most globally complete species distribution products available, validated against independent observation data with consistently better-than-chance spatial alignment (48). Restricting the analysis to birds and mammals, two of the most comprehensively assessed vertebrate groups, also means the underlying data are likely to be of comparatively high quality relative to other taxa.

Second, the HM forecasts assume that past patterns of change continue (16). They do not include changes in policy or development patterns, or other future pressures such as climate change, which could compound the direct pressures captured here. They therefore also do not capture reductions in pressure that GBF-aligned action would be intended to produce. ETA as presented here is best read as a baseline against which the effect of future policy can be measured.

Outputs at both levels should be interpreted alongside their

spatio-temporal uncertainty and treated as indicative rather than definitive for any individual species or place, to be combined with other lines of evidence such as local knowledge and monitoring data.

A framework open to development. The framework rests on four components: a cumulative pressure forecast, species-specific exposure thresholds, aggregation across species or across a species' range, and an uncertainty envelope. Combining exceedance across co-occurring species within a pixel gives the community-level ETA presented here. The same thresholds can instead be tracked across each species' range to characterize exposure for individual species, which can then be summarized across species, for example by Red List category or within ecoregions. The global application uses areas of habitat (47) and a deep-learning HM forecast (16), with lower and upper trajectories that bound its 95% prediction interval, but each component can be substituted. Locally derived range estimates from occurrence data, whether from camera traps, eDNA, bioacoustic monitoring or field surveys, can replace the AOH layer where such data exist. Threat-specific forecasts could be matched to the threats that affect each species, building on approaches developed for current pressures (5). Scenario-based inputs, such as the land-use projections under alternative socio-economic pathways used in global biodiversity model comparisons (9), would show when exposure could arrive under different policy futures. The forecast and ETA can be re-run whenever the HM time series is extended (4), moving the framework toward the iterative, near-term forecasting that management decisions require (16, 19). Each of these substitutions can sharpen the global results presented here for a particular region or question.

From urgency to action. Existing biodiversity metrics show where pressure is high. ETA shows when that pressure could move local species communities beyond their baseline, and how certain that timing is. Conservation budgets are finite (2). Under continued pressure, some probability of future exposure exists almost everywhere, so the question is rarely whether an area is at risk. It is where and when limited resources should be deployed to the greatest effect. As the GBF's 2030 and 2050 milestones approach, this temporal dimension is central to sequencing conservation action across competing priorities, not to excluding any area from future consideration. ETA distinguishes where biodiversity was already under pressure beyond its baseline by 2020, where it could be exposed by 2030 and 2040, and where there is still time to act. Humanitarian organizations already tie pre-agreed actions and funds to forecast triggers, an approach proposed for conservation to anticipate extreme weather (49) but not yet adopted by international conservation organizations (19). ETA could be a step toward such forecast-based action for longer-term pressures, for example by helping to identify where additional assessment, monitoring or advance planning may be warranted. The task ahead should not simply be to identify where biodiversity is at risk, but ensuring that the growing urgency of that risk is matched by the time-

liness of the response.

Experimental Procedures

Overview. We structure the analysis in five steps: (1) characterizing species-specific HM exposure thresholds from baseline range conditions; (2) detecting per-pixel exceedance of those thresholds under historical and forecasted HM. From this shared basis, two parallel analyses follow: (3) aggregating exceedance to community proportions and defining ETA as the first year the community exceedance criterion is met, and (4) computing, for each species, the cumulative proportion of its range exceeding its threshold over time. Finally, (5) aggregating results from both analyses to ecoregional units, evaluating the median per-pixel proportion of species exceeded and the number of species with $\geq 20\%$ of their in-ecoregion range exceeding their threshold, together with ecoregion naturalness and protection level, to identify sites that are still low modified, face high future risk to species or communities, and have a large protection gap. All analyses were conducted at 1 km resolution in Mollweide equal-area projection (EPSG:54009) and displayed in Robinson projection, on a fixed global grid (1 km pixels, origin at $-18,000,000$ m, $8,570,000$ m) to ensure consistent pixel boundaries across all raster operations.

Data sources. Our analysis was conducted at the global scale, encompassing all terrestrial ecosystems where human modification pressure and species distributions were available through the Area of Habitat (AOH) framework (4, 47). Species distribution data were obtained from global AOH maps (47), representing suitable habitat for 16,132 terrestrial mammals and birds. AOH rasters were harmonized from 100 m to 1 km resolution and projected to the Mollweide coordinate system. After excluding species with missing data or mapped areas ≤ 10 km², as well as the species classified as extinct or extinct in the wild according to the IUCN Red List of Threatened Species (50), 15,924 species were retained. Areas are reported as a percentage of land within RESOLVE ecoregions (30) with 2015 HM data (132.0 million km², excluding Antarctica and open water), based on counts of 1 km² pixels on the equal-area grid.

Species-level threshold estimation. Following the approach of Trisos et al. (13), we quantified each species' exposure to HM across its range in the past and assessed projected changes in the future. Human modification data were derived from the Global Human Modification map (HM) for 1990–2020 at 5-year intervals, resampled from 300 m to 1 km (4). HM quantifies 16 anthropogenic threats classified under the IUCN threat taxonomy, combined into a cumulative 0–1 score representing the proportion of a landscape area modified by humans. Future HM trajectories were obtained from global probabilistic forecasts produced by a convLSTM model trained on the observed spatial and temporal dynamics, forecast at 1 km resolution and 5-year intervals from 2025 to 2040 (16). We used three separately modeled forecast trajectories at each pixel to characterize its likely outcome as

well as the plausible range of future pressures: a mean trajectory, and lower and upper trajectories corresponding to the 2.5th and 97.5th percentiles of the forecast, which bound a 95% prediction interval. In regions withheld from model training, these intervals contained 97.2%, 96.1%, 94.4% and 95.9% of observed HM values at forecast horizons of 5, 10, 15 and 20 years, respectively, indicating well-calibrated uncertainty (16). Validation also showed that the mean forecast systematically underpredicts large increases in HM, which are rare and often occur with limited preceding signals (16). These forecasts assume that the spatial and temporal patterns of HM change observed in the historical record (1990–2020) continue, without changes in policy or development patterns. Because the upper and lower bounds are estimated independently at each pixel, the upper trajectory should not be interpreted as a single spatially coherent worst-case scenario in which all locations simultaneously experience their most extreme plausible outcome. Rather, it indicates how bad conditions could plausibly become at a given location, and the resulting map is best read as an envelope of risk rather than a forecast of a specific joint global future. Forecast layers were reprojected to Mollweide projection and aligned to the 1 km analysis grid prior to analysis.

For each species, we extracted HM values within its AOH for the baseline year 2015, selected because the AOH refinement process used a land-cover dataset from that year (47). We then characterized the distribution of HM values across occupied pixels and defined the 95th percentile as the upper threshold of each species' HM niche. The threshold is defined as an absolute HM value, following the realized-niche framing of Trisos et al. (13): exceedance identifies conditions outside the boundary of HM levels a species has already experienced, rather than the magnitude of change a pixel has undergone. A relative-change metric would instead capture the rate of pressure increase, which need not correspond to whether conditions have moved outside a species' range-wide realized niche. We used the 95th rather than the maximum percentile to reduce sensitivity to outlier pixels, which at 1 km resolution and across multi-year intervals may reflect transient or spatially unrepresentative high-modification events. The resulting species-specific HM thresholds were treated as exposure limits and subsequently used to detect exceedance under future HM scenarios.

Detection of exceedance. For each year (2015–2040, at 5-year intervals), we classified pixels as exceeded where HM values met or exceeded the corresponding species-specific threshold (binary outcome: 1 = exceeded, 0 = not exceeded).

Community-level aggregation and Estimated Time to Act (ETA). Per-pixel exceedance proportions were calculated by aggregating individual species pixel exceedance:

$$P_{ij} = \frac{E_{ij}}{S_i}, \quad (1)$$

where P_{ij} is the proportion of species exceeding their upper 95th percentile HM value from 2015 in pixel i at year j , E_{ij}

is the number of species exceeding their threshold, and S_i is the total number of species whose AOH overlaps with the pixel.

ETA was defined as the first assessed year in which the community exceedance criterion was met, with at least 30% of the species present in a pixel beyond the upper end of their baseline exposure. Assessed years are 2015 and 2020, for which HM is observed, and the forecast steps 2025, 2030, 2035 and 2040; 2015 and 2020 are reported together as “by 2020”. We set this criterion a priori, as evidence for any particular community-level share at which community function or persistence changes abruptly is limited. Responses to global change generally increase gradually with pressure, with abrupt shifts rarely detected in empirical data (51), and the effects of species loss on ecosystem functioning likewise scale with the level of loss (52). The criterion therefore serves as a defined reference point for ranking rather than as a level at which ecological change is expected. It refers to exposure beyond each species' own baseline rather than to species loss, which exposure does not by itself imply. ETA is designed to show where and when community-level exposure is projected to occur, making differences in urgency between locations visible and allowing the spread of that urgency across space and time to be examined, in support of spatial prioritization of conservation action. The exceedance proportion shows what share of the species in a community is exposed at a given time, and the forecast envelope shows how confident that timing is and how high exceedance reaches in the upper estimates. Neither measures the impact of exposure on species. Under this framework, the choice of community criterion can affect both the ETA assigned to a pixel and whether a pixel reaches ETA within the forecast window (2015–2040) rather than being assigned >2040, particularly in areas where HM changes slowly. To characterize uncertainty and potential upper-bound risk, ETA was evaluated using the lower, mean and upper forecasts of human modification. We report all three trajectories in the Supplementary Information. The main text emphasizes the upper trajectory, which captures the higher-risk exposure most relevant to precautionary conservation planning (see Discussion).

Species-level exceedance analysis. We complemented the community-level, pixel-based analysis with a species-level analysis, tracking exceedance across each species' AOH to characterize risk profiles for individual species under cumulative human modification pressure. This analysis was applied to all 15,924 retained terrestrial mammals and birds. Species were grouped by IUCN Red List category (50): threatened (Critically Endangered, CR; Endangered, EN; Vulnerable, VU; $n = 2,157$), Near Threatened (NT), Least Concern (LC) and Data Deficient (DD). Species whose names could not be matched to a Red List category were kept and labeled “Unclassified”.

For every species we used the same per-pixel procedure. Within each species' AOH, a pixel was marked as exceeded in a given year (2015, 2020, 2025, 2030, 2035, 2040) if its HM value met or exceeded the species-level threshold (defined above from the 2015 baseline). By construction, ap-

proximately 5% of each species' range already exceeds this threshold in 2015, a direct consequence of setting the threshold at the 95th percentile. We applied this under the mean, lower (2.5th-percentile) and upper (97.5th-percentile) HM trajectories. For each pixel we recorded the first year in which the threshold was met or exceeded. For each species and each year we then calculated the cumulative proportion of its AOH exceeding its threshold, meaning the share of AOH pixels whose first year of exceedance is at or before that year. In doing so, we report a proportion of pixels rather than an exceeded area. For each Red List category, we summarized the species-level cumulative proportions of AOH pixels exceeding their threshold as the median and interquartile range (IQR) across species, at each year.

Ecoregion-level assessment. To understand how community-level and species-level exceedance jointly relate to conservation urgency, we summarized these characteristics for RESOLVE ecoregion boundaries (30). This allows us to characterize where communities and species in still-natural ecoregions might face high exposure, across species and within their ranges, alongside current protection status. For each ecoregion, we summarized mean 2020 HM and derived current naturalness as $1 - \text{HM}$, using the same HM class boundaries applied elsewhere in this study: high naturalness ($\text{HM} \leq 0.1$, $\text{naturalness} \geq 0.9$), moderate naturalness ($0.1 < \text{HM} \leq 0.4$, $0.6 \leq \text{naturalness} < 0.9$) and low naturalness ($\text{HM} > 0.4$, $\text{naturalness} < 0.6$).

We summarized exposure for each ecoregion using two impact metrics. We considered community-level exposure by computing, for each ecoregion, the median per-pixel proportion of the local species community exceeding its threshold, under the upper-trajectory forecasts for the target year 2040. We complemented this with a species-level assessment. For every species–ecoregion pair, we intersected the species' AOH with the RESOLVE ecoregion boundaries, and within that intersection identified the pixels above the species' own 2015 95th-percentile HM threshold, based on the upper estimates for 2040. This gave the species' in-ecoregion area of habitat and the share of it above that threshold. In-ecoregion fragments $\leq 10 \text{ km}^2$ were excluded as non-meaningful presence. A species was classified as impacted within an ecoregion if at least 20% of its in-ecoregion area of habitat was above its threshold by the target year. This criterion applies to the part of each species' AOH that lies within the ecoregion, regardless of how large that part is relative to the species' total AOH, so a species is counted equally in every ecoregion where it meets the criterion, and the count is not weighted by the share of its AOH in each ecoregion. Summing these species gave the number of species at risk in each ecoregion. For each impact metric, we ranked the 822 ecoregions and divided them into equal-count terciles, so the top tercile comprises the 274 ecoregions with the highest values on that metric. Because this assessment is intended to illustrate how exceedance estimates can inform precautionary prioritization, rather than to further characterize trajectory sensitivity, we report ecoregion results based on the upper estimates only. For each ecoregion, we calculated the proportion of land area

under protection using the World Database on Protected Areas and the World Database on Other Effective Area-based Conservation Measures (WDPA and WD-OECM; February 2026) (53). From the WDPA, we retained all non-marine sites (terrestrial and coastal) with a status other than “Proposed” (i.e. designated, inscribed, established or adopted) and an IUCN management category other than “Not Applicable”. All OECMs from the WD-OECM were added to this layer. The combined layer was dissolved to remove overlaps between sites, then intersected with each ecoregion polygon, and protected area was expressed as a percentage of ecoregion area.

Technical implementation. All spatial processing was conducted in Google Earth Engine using the Python API, enabling scalable global computation. Visualization and post-processing analyses were performed in QGIS and Python, respectively. Source code will be made available at <https://github.com/MariaVoigt/ETA> with journal submission.

Resource availability. Data will be made available with journal submission.

Author contributions

M.V. led the analysis and writing. M.V., C.M.K., G.R.M. and J.R.O. conceptualized the study and designed the analysis. M.V. performed the analysis, wrote the code and produced the figures. G.R.M. supervised the analysis. C.M.K. and J.K. supervised the project and acquired funding. All authors contributed to interpreting the results and to writing and revising the manuscript.

Competing financial interests

The authors declare no competing interests.

ACKNOWLEDGEMENTS

Funding to support this work was provided by The Nature Conservancy.

AI statement

Claude models (Anthropic; Sonnet 5.5, Opus 4.8, 5.0, and 5.5) were used to check spelling and grammar, improve the style and clarity of the manuscript, and review earlier drafts. Claude Code was also used to assist with analysis development and code generation. All AI-assisted outputs were reviewed and verified by the authors, who take full responsibility for the content of the manuscript.

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Supplementary Information

Table S1. Area and median human modification (HM) in 2015 and projected values in 2040, with absolute and relative changes by HM class and forecast trajectory.

HM class (2015)	Area (km ² ; % of land)	Trajectory	Median HM, 2015	Median HM, 2040	Absolute change (Δ HM)	Relative change (%) [*]
Overall	132,039,790 (100.0%)	Upper	0.0194	0.0996	+0.0802	–
		Mean		0.0271	+0.0077	–
		Lower		0.0097	–0.0097	–
Low (HM $\leq$ 0.1)	93,453,506 (70.8%)	Upper	0.0041	0.0527	+0.0485	–
		Mean		0.0096	+0.0054	–
		Lower		0.0002	–0.0040	–
Moderately modified (0.1 < HM $\leq$ 0.4)	28,083,357 (21.3%)	Upper	0.2158	0.4004	+0.1846	+85.5
		Mean		0.2598	+0.0439	+20.4
		Lower		0.1816	–0.0342	–15.8
Highly modified (HM > 0.4)	10,502,927 (8.0%)	Upper	0.4941	0.6973	+0.2031	+41.1
		Mean		0.5488	+0.0547	+11.1
		Lower		0.4668	–0.0273	–5.5

Notes: HM is a dimensionless index from 0 to 1. Class boundaries follow Fig. 1: low, HM $\leq$ 0.1; moderately modified, 0.1 < HM $\leq$ 0.4; highly modified, HM > 0.4. Areas and medians are calculated over land within RESOLVE ecoregions with 2015 HM data (132,039,790 km², excluding Antarctica and open water). Absolute change is the difference between the 2040 and 2015 medians; relative change is this difference divided by the 2015 median, multiplied by 100. Changes were calculated from unrounded values. Upper and lower trajectories are the 97.5th and 2.5th percentiles of the forecast. ^{*}Relative change is not reported for the overall and low-modified classes, as their 2015 median HM is close to zero, so small absolute changes produce large and unstable percentages; absolute change (Δ HM) is reported instead.

Table S2. Species-exceedance-proportion distribution by year, forecast trajectory, and 2015 Human Modification class (median and 5th–95th percentiles). See Fig. 1B and Table S1 for the 2015 HM-class land-area breakdown.

Year	HM trajectory	HM 2015 class	Median species exceedance proportion (%)	5th–95th percentile species exceedance proportion (%)
2015	Observed	Low	0.01%	0.01% – 1.86%
		Moderate	0.08%	0.08% – 23.82%
		High	10.53%	0.23% – 57.41%
2020	Observed	Low	0.01%	0.01% – 1.86%
		Moderate	1.14%	0.13% – 33.21%
		High	29.29%	1.17% – 97.22%
2025	Lower	Low	0.00%	0.00% – 0.00%
		Moderate	0.11%	0.11% – 23.04%
		High	12.86%	0.29% – 93.35%
	Mean	Low	0.01%	0.01% – 2.72%
		Moderate	1.14%	0.13% – 40.22%
		High	33.99%	1.17% – 97.22%
	Upper	Low	0.02%	0.02% – 8.19%
		Moderate	3.50%	0.17% – 62.09%
		High	60.54%	5.86% – 98.01%
2030	Lower	Low	0.00%	0.00% – 0.00%
		Moderate	0.11%	0.11% – 23.04%
		High	16.01%	0.30% – 94.12%
	Mean	Low	0.01%	0.01% – 3.44%
		Moderate	1.94%	0.14% – 45.70%
		High	41.79%	2.71% – 97.22%
	Upper	Low	0.02%	0.02% – 11.31%
		Moderate	9.76%	0.18% – 80.08%
		High	83.98%	16.79% – 98.01%
2035	Lower	Low	0.00%	0.00% – 0.00%
		Moderate	0.10%	0.10% – 23.04%
		High	20.70%	0.31% – 95.68%
	Mean	Low	0.01%	0.01% – 5.06%
		Moderate	1.94%	0.14% – 48.82%
		High	45.69%	2.71% – 97.22%
	Upper	Low	0.03%	0.03% – 16.80%
		Moderate	19.91%	0.19% – 90.23%
		High	94.16%	41.01% – 98.76%
2040	Lower	Low	0.00%	0.00% – 0.00%
		Moderate	0.10%	0.10% – 19.13%
		High	16.79%	0.30% – 95.68%
	Mean	Low	0.01%	0.01% – 5.06%
		Moderate	1.94%	0.15% – 53.51%
		High	53.51%	3.52% – 97.23%
	Upper	Low	1.14%	0.05% – 23.81%
		Moderate	25.35%	0.19% – 92.57%
		High	94.91%	44.92% – 98.76%

Lower and Upper denote the 2.5th and 97.5th percentile bounds of the human modification forecast. 2015 and 2020 values are observed and trajectory-invariant, not forecast.

Table S3. Land meeting the 30% community exceedance criterion, by year, forecast trajectory and 2015 HM class. The criterion is met in a 1 km pixel when at least 30% of the mammal and bird species present exceed their exposure threshold (the 95th percentile of HM across their area of habitat in 2015). (A) Cumulative share of land where the criterion has been met by each year, under the lower, mean and upper trajectories; a pixel counts from the first year the criterion is met. (B) Each pixel assigned to one class according to the trajectories under which the criterion is met by 2040. (C) Land newly meeting the criterion in 2025–2040 under the mean trajectory, and under the upper trajectory only, by 2015 HM class.

(A) Land meeting the criterion by each year			
Year	Lower % of land (million km ²)	Mean % of land (million km ²)	Upper % of land (million km ²)
2020 (observed)	5.3 (7.0)	5.3 (7.0)	5.3 (7.0)
2025	5.3 (7.0)	6.1 (8.0)	9.3 (12.3)
2030	5.3 (7.0)	6.9 (9.1)	13.4 (17.7)
2035	5.4 (7.1)	7.3 (9.7)	17.8 (23.5)
2040	5.4 (7.1)	8.0 (10.6)	19.7 (26.1)
Added 2020–2040	0.1 (0.1)	2.7 (3.6)	14.5 (19.1)

(B) Agreement between trajectories by 2040 (each pixel counted once)		
Class	Area (million km ²)	% of land
Met by 2020 (observed; all trajectories)	7.0	5.3
Met 2025–2040 under all three trajectories	0.1	0.1
Met 2025–2040 under mean and upper trajectories only	3.5	2.6
Met 2025–2040 under the upper trajectory only	15.5	11.7
Not met by 2040 under any trajectory	106.0	80.3
Total	132.0	100.0

(C) Land newly meeting the criterion 2025–2040, by 2015 HM class						
HM 2015 class	Mean trajectory			Upper only		
	Area (million km ²)	% of this land	% of class	Area (million km ²)	% of this land	% of class
Low (HM ≤ 0.1)	0.2	5.6	0.2	2.7	17.2	2.8
Moderately modified (0.1 < HM ≤ 0.4)	1.6	43.8	5.6	9.6	61.8	34.1
Highly modified (HM > 0.4)	1.8	50.7	17.4	3.3	21.0	31.0
Total	3.6	100.0	–	15.5	100.0	–
% of land	2.7			11.7		

Notes: Percentages are of land within RESOLVE ecoregions with 2015 HM data (132.0 million km², excluding Antarctica and open water), based on counts of 1 km² pixels on the equal-area grid. 2020 values use observed HM and are identical across trajectories. Lower and upper trajectories are the 2.5th and 97.5th percentiles of the HM forecast and bound its 95% prediction interval. Trajectories are estimated independently for each pixel, so these areas indicate where the upper 95% estimate meets the criterion, not a single joint outcome. No land meets the criterion under the lower or mean trajectory without also meeting it under the upper trajectory, so the classes in (B) are complete. Percentages and areas are rounded independently, so sums may differ by 0.1. Fig. 2 (upper trajectory) and Fig. S2 (mean and lower trajectories) map the results in (A). In (C), the mean trajectory set is the land newly meeting the criterion 2025–2040 under the mean trajectory (the ‘all three’ and ‘mean and upper’ classes in B); the upper-only set is the ‘upper trajectory only’ class in B. ‘% of this land’ is each HM class’s share of the set; ‘% of class’ is the share of the class’s total 2015 area (Table S1).

Table S4. Species-level share of habitat exceeding the exposure threshold, by IUCN Red List category. Median, interquartile range (p25–p75), and 95th percentile of each species' own cumulative proportion of area of habitat (AOH) exceeding the exposure threshold, by IUCN Red List category, forecast trajectory, and checkpoint year (2020, 2030, 2040). Median range gives each category's median species AOH extent (km²). Δ 2020–2040 gives the change in median cumulative exceedance, in percentage points, between the 2020 baseline and 2040. N = number of species per category.

IUCN category	Trajectory	N	Median range (km ²)	Δ 2020–2040 (pp)	Period	Median (%)	IQR (p25–p75)	P95 (%)
Critically Endangered	Mean	318	1,652	+4.1	2020	5.7	5.3–6.7	10.4
					2030	8.2	6.6–10.2	18.6
					2040	9.8	7.9–13.7	30.8
	Upper			+34.6	2020	5.7	5.3–6.7	10.4
					2030	21.5	15.0–31.2	77.9
					2040	40.4	26.6–69.6	100.0
Endangered	Mean	772	2,748	+3.5	2020	5.6	5.3–6.2	8.5
					2030	7.7	6.4–9.3	14.0
					2040	9.1	7.4–11.7	20.3
	Upper			+29.5	2020	5.6	5.3–6.2	8.5
					2030	19.1	14.3–26.5	51.3
					2040	35.1	24.6–52.6	100.0
Vulnerable	Mean	1,067	23,279	+3.4	2020	5.6	5.3–6.1	7.7
					2030	7.5	6.4–9.3	13.5
					2040	8.9	7.4–11.3	18.6
	Upper			+26.1	2020	5.6	5.3–6.1	7.7
					2030	18.4	14.0–24.6	44.1
					2040	31.8	23.6–45.5	97.5
Near Threatened	Mean	1,210	28,920	+3.5	2020	5.4	5.2–5.9	7.4
					2030	7.4	6.3–9.3	12.8
					2040	8.9	7.4–11.6	17.7
	Upper			+26.4	2020	5.4	5.2–5.9	7.4
					2030	18.3	13.9–25.6	42.8
					2040	31.8	22.6–44.4	98.1
Least Concern	Mean	11,384	375,378	+3.1	2020	5.4	5.2–5.8	6.6
					2030	7.2	6.3–8.2	10.4
					2040	8.5	7.2–9.8	14.0
	Upper			+19.9	2020	5.4	5.2–5.8	6.6
					2030	15.6	12.6–19.4	30.5
					2040	25.2	20.4–33.2	74.9
Data Deficient	Mean	617	9,226	+3.5	2020	5.5	5.2–6.2	8.2
					2030	7.5	6.3–9.3	16.2
					2040	9.0	7.4–12.1	29.2
	Upper			+27.1	2020	5.5	5.2–6.2	8.2
					2030	18.4	13.7–26.9	77.5
					2040	32.7	23.7–55.5	100.0
Unclassified	Mean	556	164,434	+3.3	2020	5.4	5.2–5.8	6.9
					2030	7.2	6.3–8.5	11.1
					2040	8.6	7.3–10.4	15.5
	Upper			+21.2	2020	5.4	5.2–5.8	6.9
					2030	16.3	12.9–21.5	36.9
					2040	26.5	20.8–37.4	92.5

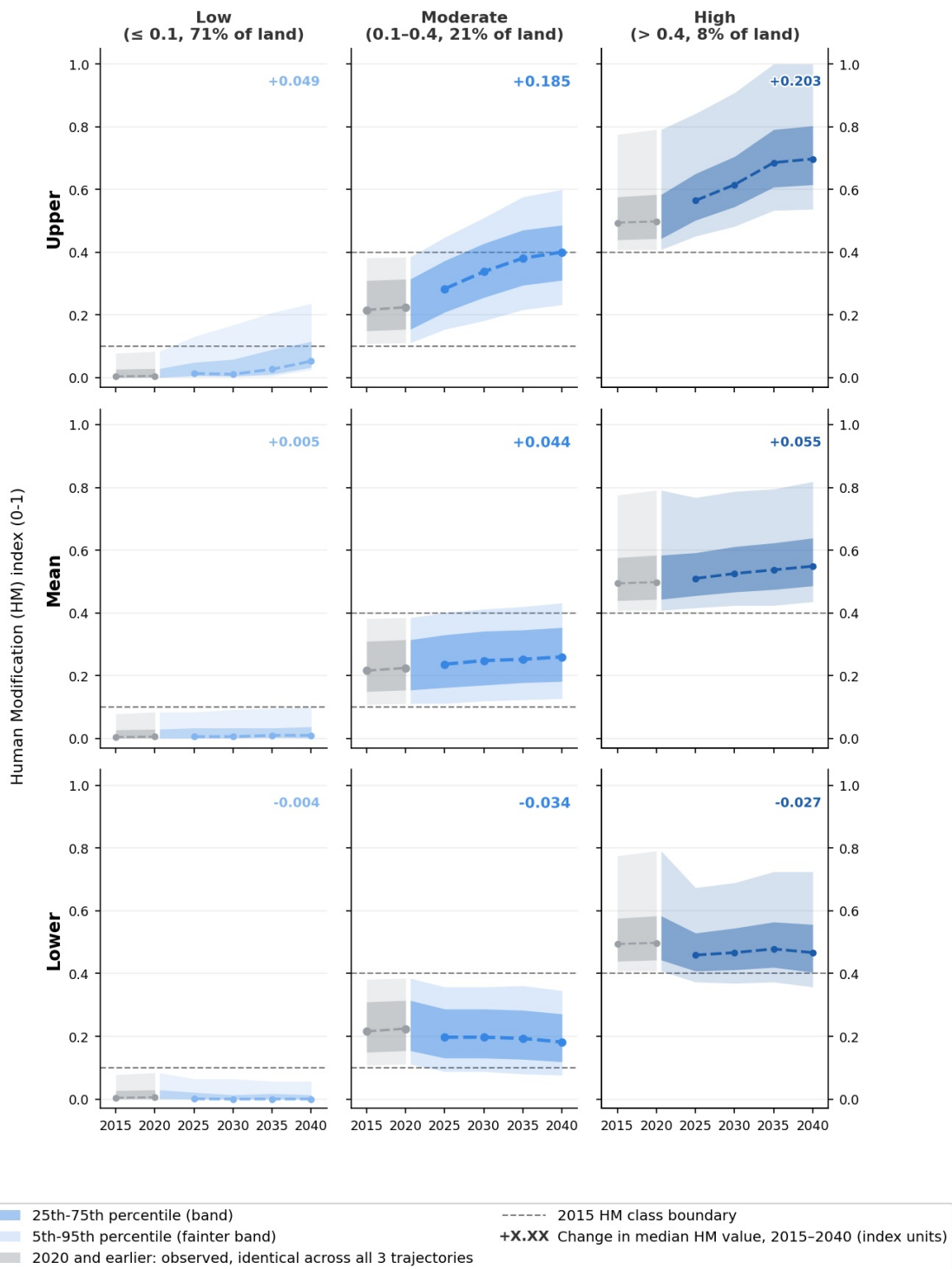


Fig. S1. Underlying Human Modification (HM) value by trajectory and 2015 HM class (Low $HM \leq 0.1$, Moderate $0.1 < HM \leq 0.4$, High $HM > 0.4$). HM values from years with observed HM shown in gray, forecast years in blue. Darker shaded area: 25th–75th percentile; lighter shaded area: 5th–95th percentile. Dashed line: median; connecting line: median HM trend across the years, with value in top-right corner showing the change in median HM value (index units) from 2015 to 2040. Horizontal dashed line(s): 2015 HM class boundaries; a band crossing this line indicates that class’s HM values have moved past the threshold used to define it in 2015.

Estimated Time to Act - Year to community exceedance

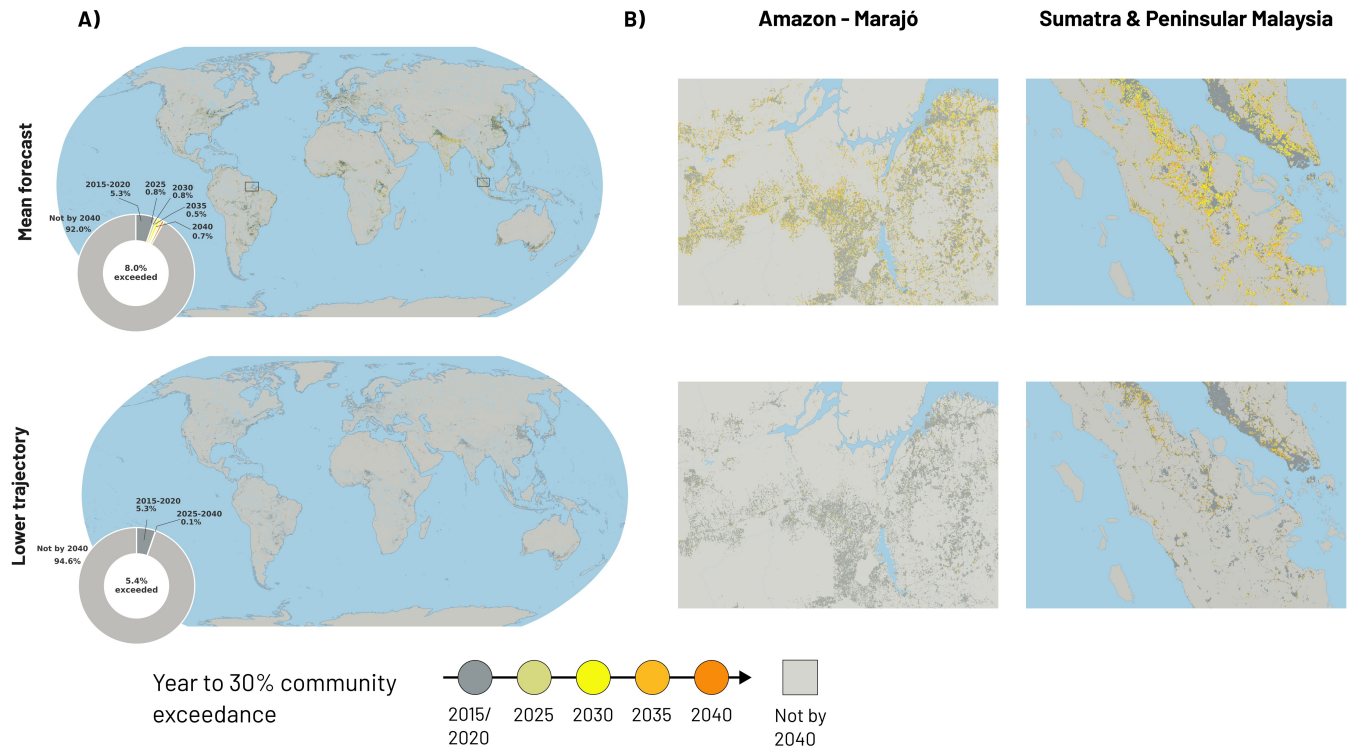


Fig. S2. Estimated Time to Act for mean and lower forecast trajectory. Dark gray are areas where at least 30% of mammal and bird species have exceeded their 2015 95th percentile HM value by 2020. Olive to orange areas exceed in the respective year from 2025 to 2040. Light gray are areas where the criterion is not met by 2040. (A) Global map displaying the distribution of year to exceedance for mean and lower forecast trajectory, with doughnut plot identifying the percent exceedance by year, and overall percent in center of plot. Segments may not sum to the total due to rounding. (B) Zoom into ETA patterns in focal regions in the Amazon delta and in Sumatra and Peninsular Malaysia.