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A global map of species at risk of extinction due to natural hazards

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An often-overlooked question of the biodiversity crisis is how natural hazards contribute to species extinction risk. To address this issue, we explored how four natural hazards, earthquakes, hurricanes, tsunamis, and volcanoes, overlapped with the distribution ranges of amphibians, birds, mammals, and reptiles that have either narrow distributions or populations with few mature individuals. To assess which species are at risk from these natural hazards, we combined the frequency and magnitude of each natural hazard to estimate their impact. We considered species at risk if they overlapped with regions where any of the four natural hazards historically occurred (n = 3,722). Those species with at least a quarter of their range subjected to a high relative impact were considered at high risk (n = 2,001) of extinction due to natural hazards. In total, 834 reptiles, 617 amphibians, 302 birds, and 248 mammals were at high risk and they were mainly distributed on islands and in the tropics. Hurricanes (n = 983) and earthquakes (n = 868) affected most species, while tsunamis (n = 272), and volcanoes (n = 171) affected considerably fewer. The region with the highest number of species at high risk was the Pacific Ring of Fire, especially due to volcanoes, earthquakes, and tsunamis, while hurricane-related high-risk species were concentrated in the Caribbean Sea, Gulf of Mexico, and northwestern Pacific Ocean. Our study provides important information regarding the species at risk due to natural hazards and can help guide conservation attention and efforts to safeguard their survival.

earthquake | conservation strategies | hurricane | tsunamis | volcanoes

Significance

This study explores the global overlap between species distributions and the occurrences of earthquakes, hurricanes, tsunamis, and volcanoes, to show that 10% of all 34,035 assessed terrestrial vertebrates (5.7% of birds, 7% of mammals, 16% of amphibians, and 14.5% of reptiles) are at risk due to at least one natural hazard, while 5.4% are at high risk. Species at high risk are mainly found in the tropics and on islands. Exposure to natural hazards can augment anthropogenic drivers, thereby compounding their impacts. Therefore, conservation strategies, such as intensive population management in situ and ex situ and the establishment of insurance populations, may become pivotal for the survival of those species in the next decades.

The critical role of biodiversity in sustaining not only natural systems but also human populations is recognized by the convention on biological diversity (CBD) (1). Yet, the extinction of species and degradation of ecosystems continue at a rate not experienced in human history (2, 3). To reverse this trend, the Parties at the CBD have recently agreed to the Kunming-Montreal Global Biodiversity Framework (1) and researchers suggested the ambitious goal of keeping the extinctions of species at a low level over the next 100 y (4). The ongoing pulse of animal species loss, also referred to as the Anthropocene defaunation (2), is mainly a consequence of direct and indirect human impacts on the planet. Nonetheless, species that are under threat from human activities often have restricted distribution or limited abundance; thus, they may also be more susceptible to extinction through natural hazards, such as earthquakes, hurricanes, tsunamis, and volcanoes (5–10).

Natural hazards are usually defined as events that overwhelm the community's resilience and have the potential to push species toward extinction (11). One example is the 2017 Hurricane Maria, which likely extirpated 239 of the remaining 250 individuals of the endemic and critically endangered imperial amazon parrot (*Amazona imperialis*) from Dominica in the eastern Caribbean Sea (12). Human-driven changes in the environment may also restrict species ranges to areas with high incidence of natural hazards, which in turn can push these species closer to extinction. For example, the critically endangered Quito rocket frog (*Colostethus jacobuspetersi*) was once widely distributed across the central and northern Andes but is now restricted to areas around the Volcán Cotopaxi, an active volcano in Ecuador that has erupted more than 50 times since 1738 (13).

To promote resilience to natural hazards, species may be translocated to other suitable habitats and have other in situ and ex situ conservation measures established, such as in the case of the Puerto Rican parrot (*Amazona vittata*), endemic to Puerto Rico in the Caribbean Sea (14, 15). Despite once being widespread and abundant, human activity and recent hurricanes nearly caused its extinction. Due to the continued risk posed by frequent hurricanes, researchers established captive breeding programs and new wild

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populations in different locations across Puerto Rico, thereby facilitating its recovery (14, 15). As these cases illustrate, identifying those species that are frequently exposed to natural hazards can be an important guide for prioritizing monitoring and for the timely implementation of in situ and ex situ conservation programs.

The overall risk of a species experiencing negative impacts from natural hazards is expected to depend on the exposure (e.g., the frequency and magnitude) to the hazard and the species' intrinsic characteristics (5–10, 12, 16–19). For example, species with reduced mobility (e.g., most amphibians and reptiles), small body size (e.g., rodents and marsupials), slow reproductive rates (e.g., tortoises, parrots), specialised habitat requirements (e.g., lowland-affiliated species), or specific dietary requirements (notably nectarivorous and frugivorous species) are likely to be more susceptible to frequent and intense natural hazard events (8–10, 16, 18, 20–22). In addition, natural hazards can also cause indirect effects that may affect nearly all taxa, by promoting habitat degradation and temporary changes in local climatic conditions (6, 7, 10, 12, 17, 20–23), altering the onset of sexual maturity (24), accelerating biological aging via changes to the immune system (25) and increasing the vulnerability to human impacts (26). These case-based observations support the need to understand risks posed by natural hazards. However, even basic knowledge on the number and distribution of species at risk due to natural hazards remains lacking at the global scale.

To address this knowledge gap, we provide an evaluation of the risk posed by natural hazards to terrestrial vertebrate species worldwide, focusing especially on those species that have limited distributions and/or occur at low numbers. First, we selected all amphibian, bird, mammal, and reptile species with a maximum population size of 1,100 mature individuals and/or those with a range size less than or equal to 2,500 km^2 based on the IUCN Red List of Threatened Species (27). Second, we constructed an estimate for the likelihood of impact from four natural hazards (earthquakes, hurricanes, tsunamis, and volcanoes) by analyzing approximately 50 y of historical data concerning the frequency and magnitude of events. We then identified all species whose ranges overlap with known occurrences of hurricanes, earthquakes, tsunamis, and volcanoes. Finally, we classified the species at "high risk" as those for which at least a quarter of their range overlapped with areas of high relative impact from at least one natural hazard.

Results

Across all amphibians, birds, mammals, and reptiles (n = 34,035), we identified 8,813 species with limited population size and/or a restricted global range size (*SI Appendix,* Fig. S2). Among those species, 42% (3,722 out of 8,813 species) overlapped with regions where one or more major natural hazard had occurred in the past 50 y (Figs. 1 and 2*A*, Table 1, and Datasets S1–S4). Of that subset

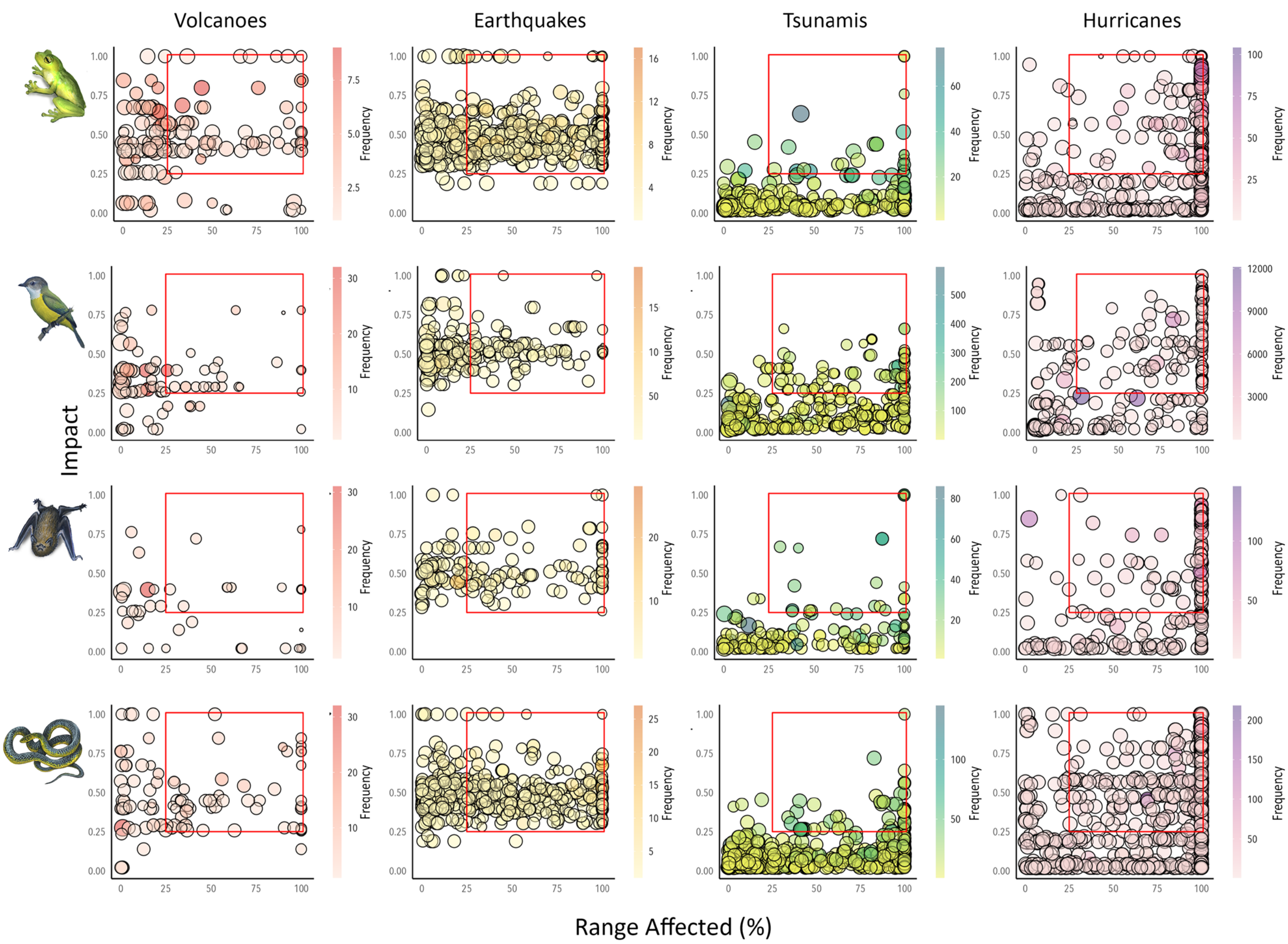


Fig. 1. Number of species ranges (1,502 reptiles, 1,183 amphibians, 632 birds, and 405 mammals) overlapping with each natural hazard and the relative weighted impact. The red square represents a subset of species (834 reptiles, 617 amphibians, 302 birds, and 248 mammals) with at least 25% of their range overlapping with areas experiencing a relative impact of at least 0.25. Varying circle sizes were employed to represent differences in log-transformed range sizes while the colours of the circles are based on the weighted frequency experienced by each species.

Table 1. Number of species that met our criteria and are considered at risk and high risk of extinction due to earthquakes, volcanoes, tsunamis, and hurricanes

	Species in earthquake zones		Species in volcanic zones		Species in tsunami zones		Species in hurricane zones	
Group	Risk	High-risk	Risk	High-risk	Risk	High-risk	Risk	High-risk
Birds	144	102	68	30	331	90	161	156
Mammals	59	85	28	11	65	89	108	118
Amphibians	207	391	79	67	269	29	294	199
Reptiles	187	290	53	63	455	64	435	510
All species	597	868	228	171	1,120	272	998	983

*Species are considered at risk when at least a small percentage of their extant geographical range overlaps with areas where natural hazards are frequent. Species are considered at high risk when at least 25% of their extant geographical range overlaps with areas experiencing a relative impact of at least 0.25.

of 3,722 species, 54% (2,001 species) were at high risk due to natural hazards (Figs. 1 and 2*B*, Table 1, and Datasets S1–S4).

The 2,001 high-risk species were mainly distributed in the Neotropics (~34%), followed by the Indomalayian (~31%) biogeographic realm (Datasets S1–S4). Almost 70% (615 reptiles, 267 amphibians, 266 birds, and 207 mammals) were only found on islands (Datasets S1–S4). Of the 2,001 high-risk species, 16% (129 reptiles, 86 amphibians, 69 birds, and 27 mammals) overlapped with regions where two or more major natural hazards have high incidence (Datasets S1–S4). Importantly, according to the latest IUCN assessment of the species, approximately 30% (247 amphibians, 171 reptiles, 98 mammals, and 89 birds) of the high risk species have their entire known range outside protected areas and a specific conservation plan was identified for only 15% (297 species; Datasets S1–S4).

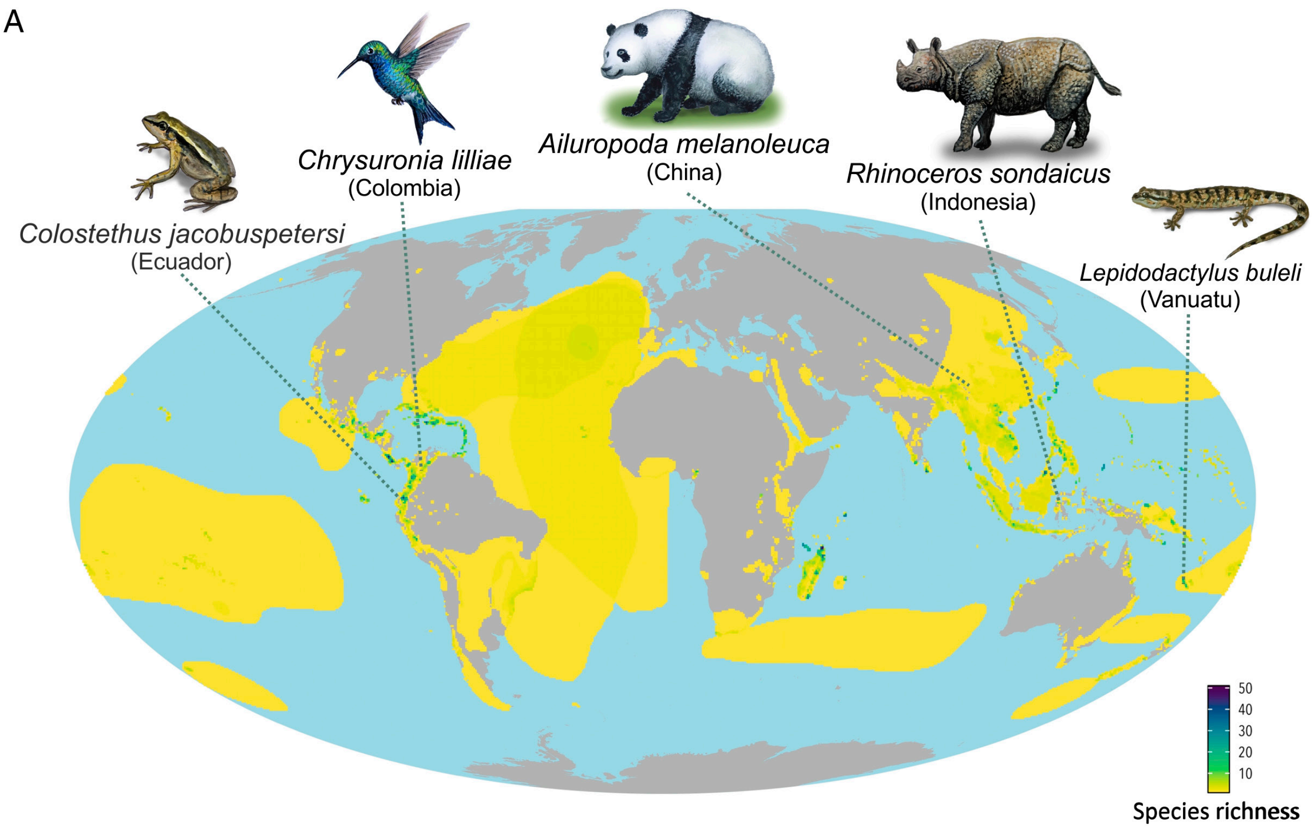
Most species at high risk were reptiles (834), followed by amphibians (617), birds (302), and mammals (248) (Fig. 2*B*, Table 1, *SI Appendix,* Figs. S3–S6, and Datasets S1–S4). Hurricanes were the most prominent natural hazard in our dataset, overlapping with 49% (983 species out of 2,001) of the high-risk species, followed by earthquakes 43% (868 species out of 2,001), tsunamis 13% (272 out of 2,001), and volcanoes 8% (171 out of 2,001) (Table 1, and *SI Appendix,* Figs. S7–S22, and Datasets S1–S4). The highest numbers of species at high risk due to volcanic, earthquake, and tsunami activities were located in the "Ring of Fire" along the Pacific Ocean and adjacent areas while hurricane-prone species were located primarily in the Caribbean Sea, Gulf of Mexico, and northwestern Pacific Ocean (Fig. 3).

Discussion

In this first attempt to provide a global map of species at risk of extinction due to natural hazards, we identified 2,001 terrestrial vertebrate species that met our threshold of high risk of extinction due to one or more natural hazards. Although these species were found to be distributed across the world, they were focused on tropical regions and the majority were located on islands. The restricted geographic range of island-dwelling species is compounded by the propensity of natural hazards to impact tropical archipelagos characterized by high level of extinctions since colonization by humans (28). This highlights the multifaceted pressures experienced by species on tropical islands.

Species endemic to tropical islands, as well as all other areas with high probability of experiencing natural hazards, have mostly evolved and persisted in natural hazard-prone environments (5, 10). Therefore, the evolutionary histories of these species may have shaped their capacity to respond to natural hazards (29), such as the evolution of generalized feeding habits (5, 28). Species surviving past natural hazards might thus be more likely to persist in the face of future but analogous exposure to natural hazards (5, 30). However, generalized feeding habits and other adaptations that have prevented species from becoming extinct due to recurrent exposure to natural hazards (e.g., high dispersal ability, early maturation, a greater number of offspring and/or many reproductive events during a lifetime) might not be enough to survive the impacts of synergistic interactions between natural hazards and anthropogenic activities (8, 16). Thus, species with advantageous sets of traits may still fail to recover after facing climatic or geological events if their populations have already declined to small numbers or have been confined to a small geographical area. This may especially be problematic if combined with degraded habitat and fragmented landscapes (8, 16). Notably, human-modified landscapes often have restricted connectivity, which limits the ability of individuals to flee and establish populations in other locations (31). Specifically for tropical islands, human-introduced predators have driven numerous island endemics to extinction and caused many to be at high risk of extinction (28), jeopardizing their survival in the case of major natural hazard events. In addition to human impacts, climate-driven natural hazards (e.g., hurricanes) are predicted to increase in frequency and magnitude in the future (32), with unknown but probably significant impacts on biodiversity. Taken together, this highlights the need for implementing conservation measures to safeguard species at risk due to natural hazards.

Ecosystem-level conservation and restoration may effectively mitigate the long-term threat posed by natural hazards to biodiversity (33, 34) although the effectiveness of such efforts may depend on the frequency and magnitude of those events. Additionally, ecosystem-level approaches can influence the extent of human intervention necessary to manage the impacts of natural hazards on ecosystems (11). Natural barriers like mature sand dunes, mangrove forests, secondary forests, wetlands, and coral reefs, for instance, are all important elements of shore protection and flood mitigation during hurricanes and tsunamis (35, 36). Connecting native vegetation fragments and forest patches with broad corridors and establishing protected areas surrounding regions at risk, in addition to preserving existing ones, can also act to protect high-quality habitat and increase species' range occupancy, reducing extinction risk by natural hazards such as volcanoes and earthquakes (17, 31, 33). Although such comprehensive approaches may both safeguard high-quality habitats and serve as a protective measure for species seeking refuge from the impact of natural hazards, we note that some natural hazard events, and especially volcanic eruptions, may in some cases be too severe that no in situ conservation intervention may help as a safeguarding measure. Despite this there is evidence that conservation interventions at local scales can be effective in preventing extinctions, including for several of the species highlighted in our study as at risk of extinction due to natural hazards (10, 14, 37–40).



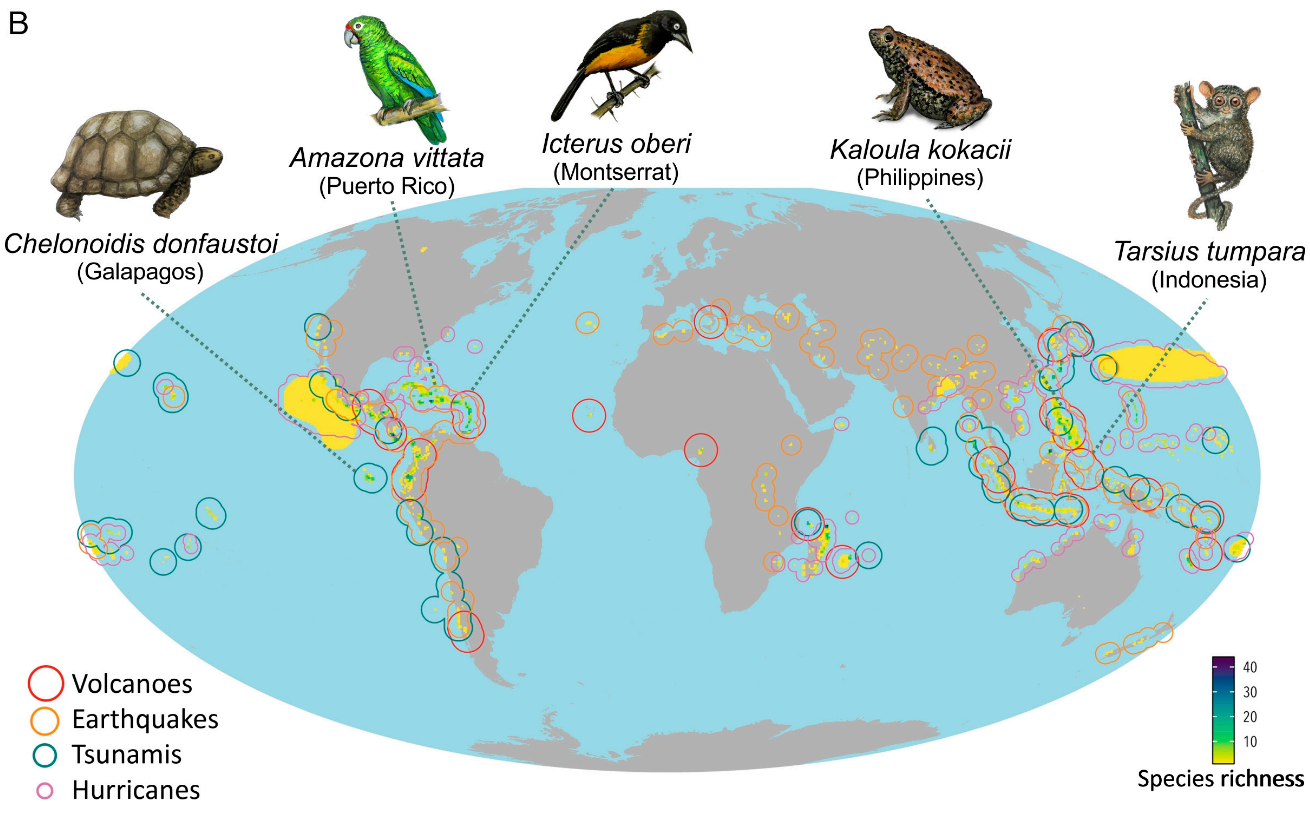


Fig. 2. Global distribution of 3,722 species that met our criteria and are considered at risk of extinction due to four natural hazards. The map shows the combined distribution of 1,502 reptiles, 1,183 amphibians, 632 birds, and 405 mammals (*Top* panel *A*). Global distribution of 2,001 species that met our criteria and are considered at high risk of extinction due to four natural hazards: volcanoes (red circle), earthquakes (yellow circles), tsunamis (green circle), and hurricanes (purple circle) (*Bottom* panel *B*). The map shows the combined distribution of 834 reptiles, 617 amphibians, 302 birds, and 248 mammals (*Bottom* panel *B*). Varying circle sizes and colors were employed to enhance the visualization of four types of hazards. The illustrations above each map represent a subset of species that met our threshold and that have already been shown to be susceptible to natural hazards.

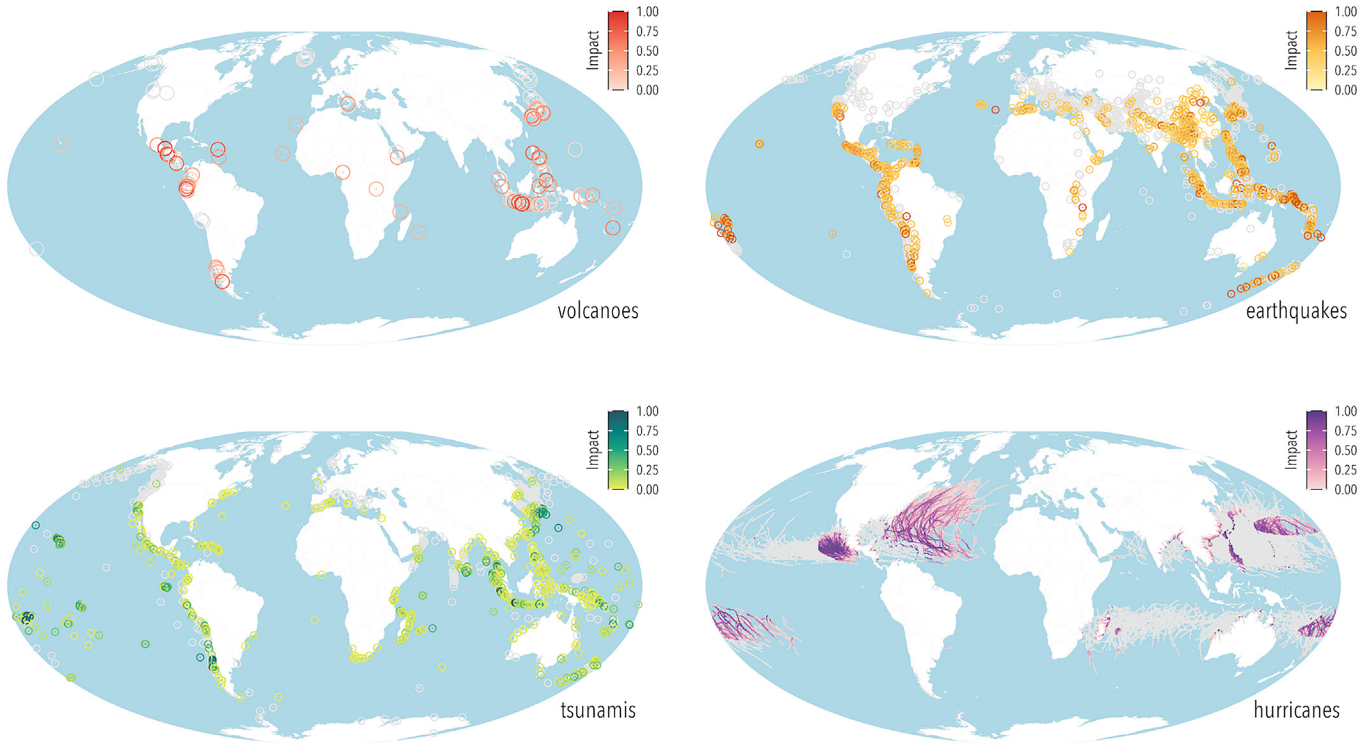


Fig. 3. The distribution of the impact of volcanoes, tsunamis, earthquakes, and hurricanes. We added buffer circles on the maps of volcanoes, tsunamis, and earthquakes for visualization purposes. For grid cells where we had impact scores but no overlap with our subset of species, we displayed them in gray.

Despite inevitably outdated information contained in some of the IUCN assessments, it is still concerning that only 15% of species at high risk of extinction due to natural hazards have conservation plans and the ranges of about 30% were not reported to be covered by any protected areas (27). Habitat protection and conservation interventions are cornerstone conservation strategies (33, 34) and successful examples include the recovery of the Puerto Rican amazon (*A. vittata*), the black robin (*Petroica traversi*), the Mauritius kestrel (*Falco punctatus*), the Visayan warty pig (*Sus cebifrons*), the takahe (*Porphyrio hochstetteri*), the Georgia blind salamander (*Eurycea wallacei*), the alligator lizard (*Abronia meledona*), the blue-sided treefrog (*Agalychnis annae*), and the akiapolaau (*Hemignathus wilsoni*) (37–45).

Conserving the species that are susceptible to being impacted by natural hazards requires an understanding of both the causes and consequences of small and fragmented populations (46); however, this information is often unavailable (46, 47). Some efforts have been made to undertake population viability analyses, taking into account the added complication of natural hazards alongside anthropogenic effects (48). Yet, we still lack basic life-history information to devise realistic population viability analyses for many of the species at high risk. Furthermore, it has also been difficult to determine the number of individuals required to avoid the fitness costs of a small population size and maintain the viability of populations (49).

In summary, assessing species' vulnerability to natural hazards is a complex process, dependent on factors such as the frequency, magnitude, nature of the hazards, and species-specific traits. Our results indicate that approximately 10% of terrestrial vertebrate species globally are exposed to at least one type of natural hazard, with a notable increased prevalence for species on islands and across the tropics. Mitigation of anthropogenic threats combined with in situ and ex situ conservation, focusing on assisted breeding and translocation, may be vital to preserve species of small global population sizes that are also exposed to natural hazards. This may especially be the case for endemic insular species, as they exist solely on one or a few specific islands, making them highly susceptible to devastating natural hazards. Therefore, we argue that continued and scaled-up investment in advocacy, habitat protection, restoration, intensive population management, targeted research, and public and local engagement is needed to diminish the impact of natural hazards on biodiversity. Given the likely synergistic, and often overlooked, interactions between natural hazards and anthropogenic drivers (8, 16), we hope that our global map of species at risk of extinction due to natural hazards will spur more research into the joint role of natural hazards and anthropogenic threats to biodiversity. Our study therefore contributes as a first-approximation of the species and areas that require intensive and urgent conservation actions to minimize extinctions and provides a timely insight directed to prevent species extinctions in line with Target 4 of the Kunming-Montreal Global Biodiversity Framework (1, 4).

Materials and Methods

Mapping the Location of Species at Risk. We obtained the ranges of all amphibians, birds, terrestrial mammals, and reptiles from the IUCN Red List of Threatened Species (27, 50). We then extracted the subset of species with a range size smaller than 2,500 km^2 and/or with a maximum population size of 1,100 mature individuals. The range size of 2,500 km^2 was used to identify species with restricted spatial distribution globally while also reducing commission error–false presence of a species by keeping the minimum size equal to or smaller than our grid size. The 1,100 individual threshold was based on the IUCN's criteria for threatened species (e.g., 1,000 mature individuals) plus an additional 10% designed to avoid excluding species because of uncertainties in the IUCN population. We also extracted from the IUCN Red List information about in situ conservation actions that were in place related to habitat protection (e.g., if the species occurs in at least one protected area), species management (e.g., if the species is subject to ex-situ conservation), if the species was distributed on islands or mainland, as well as the biogeographic realm (27). Further details about data on mapping the location of species at risk can be found in *SI Appendix*, Text.

Data on Natural Hazards. To obtain data on natural hazards, we georeferenced events involving volcanos (51), tsunamis (52), earthquakes (53), and hurricanes (54) using publicly accessible geophysical data. These natural hazards were selected due to the availability of georeferenced information, extensive scientific literature, and evidence of their significant impacts on terrestrial vertebrates (7, 8, 14–16, 18–22). We then filtered events to those that occurred between 1970 and 2016 (the latest year for which we had events for all four natural hazards), yielding 318,400 occurrences of hurricanes, 15,003 tsunamis, 1,871 earthquakes, and 239 volcanic eruptions. Since the hurricane dataset contained events which are not classified as hurricanes (e.g., storms and depressions, which are classified in categories of 0 to −5), we excluded these and included only events with a magnitude between 1 and 5, obtaining a dataset of 2,081 distinct hurricanes that, due to their dynamic nature, contributed to a total of 58,501 observations/events. We mapped all events using a 2,500 km^2 resolution to avoid commission errors at higher resolutions and calculated the frequency, total magnitude, and relative impact of each natural hazard within a grid cell. The frequency was calculated as the total number of events in each grid cell, and the magnitude was calculated as the sum of the magnitudes scores. The magnitude of the events of all types of hazards were standardized to a 1 to 10 scale to allow us to compare across hazards. Since there was no information on the spatial extent of all events, we considered that the extent of a hazard had the potential to impact the entire grid cell covering an area of 2,500 km^2. Further details about data on natural hazards can be found in *SI Appendix*, Text.

Calculating the Relative Impact of Natural Hazards. To calculate the probability of occurrence of an event for each natural hazard in a given year within a specific 2,500 km^2 grid cell, we used a binomial regression with a logit link function. In this analysis, the dependent variable was the presence or absence of a hazard in a given year, with this event weighted by its magnitude. After exploring alternative weighting schemes (*SI Appendix*, Text), we adjusted the models to accommodate the assumption that a single and strong event should have a higher magnitude as well as account for years with multiple events. Furthermore, as observations with no weight (e.g., years during which no hazards were observed) were discarded by our model, we assigned the lowest magnitude (a value of 1 after standardization) between 1970 and 2016 for these observations.

We calculated the probability of impact for each grid cell using the following equation:

$$I = \mathrm{glm}(F \sim 1, \text{weights} = M, \text{family} = \text{''binomial''}),$$

where I is the relative impact, F is the binary variable of occurrence or not of a specific hazard in a given year (between 1970 and 2016), and M is the scaled magnitudes of the hazards in each year. To give higher weight to events with higher magnitudes in relation to events with lower magnitudes, we squared the magnitude values. To account for years where there were multiple events, we summed the magnitudes before squaring them. The relative impact of natural hazards varies between 0 (indicating a low impact) and 1 (indicating a high impact). Further details about the calculation of the relative impact of natural hazards and the exploration of alternative weighting schemes can be found in *SI Appendix*, Text.

Identifying Species Exposure to Natural Hazards. We identified species exposed to natural hazards by intersecting the range of each species with the occurrences of natural hazards. To account for potential errors of commission and omission in the IUCN range maps, we tested two approaches: 1) estimating the percentage of the ranges intersecting with each cell and 2) conducting binary pixel-based analyses, using the entire cell area is a species range intersected it. Here, we provide the results of the former approach and in supplementary materials we provide the latter. Species were classified as high risk if at least 25% of their geographic range overlapped with areas subjected to at least 0.25 of relative impact of natural hazards. The impact of each threat was estimated by calculating the median impact across the cells with hazards that overlapped with the range of a species. We used this threshold value to categorize species at high risk by natural hazard because they have been previously used in spatial ecology and conservation prioritization of terrestrial vertebrates at different scales (7, 8, 16). Further details about data on species exposure to natural hazards and the results on regarding the binary exposure approach can be found in *SI Appendix*, Text.

Data, Materials, and Software Availability. All data and code needed to evaluate the results and conclusions in this paper are freely available within the supplementary material, Dryad (55), and GitHub (56) https://github.com/harithmorgadinho/natural_hazards. All other data are included in the manuscript and/or supporting information.

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