Pinpointing and preventing imminent extinctions

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Slowing rates of global biodiversity loss requires preventing species extinctions. Here we pinpoint centers of imminent extinction, where highly threatened species are confined to single sites. Within five globally assessed taxa (i.e., mammals, birds, selected reptiles, amphibians, and conifers), we find 794 such species, three times the number recorded as having gone extinct since 1500. These species occur in 595 sites, concentrated in tropical forests, on islands, and in mountainous areas. Their taxonomic and geographical distribution differs significantly from that of historical extinctions, indicating an expansion of the current extinction episode beyond sensitive species and places toward the planet's most biodiverse mainland regions. Only one-third of the sites are legally protected, and most are surrounded by intense human development. These sites represent clear opportunities for urgent conservation action to prevent species loss.

biodiversity | conservation | protected area | threatened species

Recent human-induced extinction rates are 100-1,000 times the geological background rate and are predicted to increase another 10-fold (1). In response, 188 countries have committed to slowing global biodiversity loss (2). Over the long term, achieving this ambitious goal requires broadscale, proactive conservation to protect entire ecosystems before their component species become threatened (3). Many species, however, are already so endangered by human activities that they will likely disappear without immediate site-specific action. Preventing these extinctions must be part of any global strategy to reduce biodiversity loss.

Among the species of primary conservation concern are those that are both highly threatened and restricted to single locations. The sites containing such species represent the extremes of two widely accepted principles for prioritizing conservation action: threat (i.e., the likelihood that the biodiversity in that site will be lost) and irreplaceability (i.e., the degree to which options for conservation are lost without the site) (4). With small populations, extreme vulnerability to habitat destruction, and limited options for conservation, these species face imminent extinction in the absence of appropriate conservation action. Furthermore, immediate requirements for their conservation are relatively straightforward; although a variety of conservation activities may eventually be needed, the obvious immediate goal is to conserve habitat in their single remaining sites.

To locate such species, we examine five major taxa for which global data are available (i.e., mammals, birds, selected reptiles, amphibians, and conifers) and identify sites that (*i*) contain at least one highly threatened species, (*ii*) represent essentially the sole area of occurrence for the species, and (*iii*), permit management as a discrete unit. (Hereafter, we refer to places that meet these criteria as "sites" and to species that trigger them as "trigger species.") Using the resulting data set, we examine the taxonomic and geographic distributions of trigger species and sites, and we compare them with the distributions of historical extinctions to examine shifts in extinction risk over time. We also determine protection status of current sites, assess levels of surrounding human activity, and estimate the costs required to adequately conserve them. These analyses are intended to complement and inform ongoing efforts to conserve global biodiversity (5–10) by identifying sites where urgent conservation action can help to prevent species extinctions.

Methods

We applied three criteria to identify sites. First, a site must contain at least one endangered or critically endangered species, as listed on the 2004 World Conservation Union (IUCN) Red List of Threatened Species (www.iucnredlist.org). A site cannot be designated on the basis of unlisted or unevaluated species, data deficient species, or vulnerable species. A site may be designated as the only suitable reintroduction site for a species assessed as extinct in the wild; only two sites were triggered by this criterion. We adopted the taxonomy followed by the IUCN Red List at the species level and did not identify sites for subspecies or subpopulations.

Second, a site must (*i*) be the sole area where an endangered or critically endangered species occurs, (*ii*) contain the overwhelmingly significant (more than ≈95% of the global population) known resident population of the species, or (*iii*) contain the overwhelmingly significant known population for one life-history segment (e.g., breeding or nonbreeding) of the species. Less than 10% of all sites were triggered by (*ii*), and only 15 sites (2 for migratory birds and 13 for breeding seabirds) were triggered by (*iii*).

Third, a site must have a definable boundary, within which habitats, biological communities, or management issues share more in common with each other than they do with those in adjacent areas (e.g., a single lake, mountaintop, or forest fragment). The boundary of the area was defined to correspond to the most practical conservation unit, including considerations of contiguous habitat, management units, and the potential for significant gene flow among populations. There was no explicit size criterion for sites, but median size of sites for which size

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Abbreviation: IUCN, World Conservation Union.

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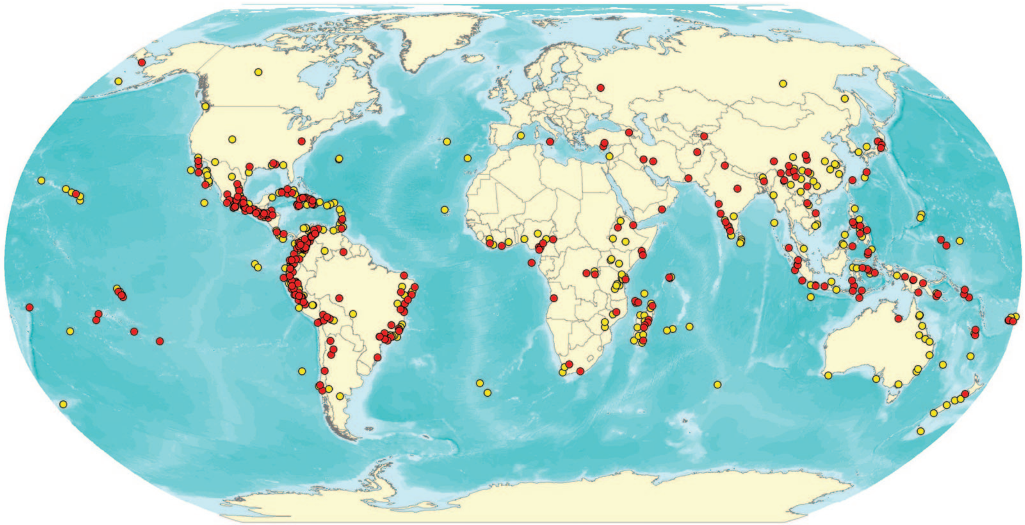

Fig. 1. Map of 595 sites of imminent species extinction. Yellow sites are either fully or partially contained within declared protected areas ($n = 203$ and 87, respectively), and red sites are completely unprotected or have unknown protection status ($n = 257$ and 48, respectively; see *Methods*). In areas of overlap, unprotected (red) sites are mapped above protected (yellow) sites to highlight the more urgent conservation priorities.

information was available was 12,060 hectares. Although this site definition is not fully objective and repeatable, it balances scientific objectivity with management practicality and follows the methodology applied in studies in refs. 9–11.

Data on species' threat were taken from the 2004 IUCN Red List of Threatened Species (www.iucnredlist.org). To reduce geographic biases, we limited our analyses to taxa that have been globally assessed by the IUCN Red List. Cycads, the only other globally assessed taxon, will likely be incorporated into the data set next year. For reptiles, only three clades have been globally assessed (i.e., order Testudines, order Crocodylia, and family Iguanidae), representing ≈4% of all reptile species (www.reptile-database.org). We do not claim these clades to be representative of overall patterns of reptile diversity and threat; we included them simply in an effort to use all available suitable information. However, pooled species richness of these three clades is significantly correlated with overall richness of reptiles (www.worldwildlife.org/wildfinder), both among biogeographic realms (Pearson's correlation coefficient; $r_7 = 0.79$, $P = 0.035$) and among terrestrial ecoregions ($r_{799} = 0.64$, $P < 0.0001$) (12, 13).

Distribution data for critically endangered and endangered species were gathered from primary literature, data compilations (main sources include www.iucnredlist.org, www.globalamphibians.org, and refs. 14–17), and consultations with experts (specific sources available upon request). Because data quality and resolution varied widely among species, each species was evaluated individually by one or more authors against the second and third criteria, and then reviewed by at least one regional expert. (see *Supporting Text*, which is published as supporting information on the PNAS web site, for discussion of data uncertainty).

To assess protection status of each site, we initially used a geographic information system to compare sites with the 2004 World Database of Protected Areas (http://maps.geog.umd.edu/WDPA/index.html). Uneven reporting among countries and inaccuracies or gaps in spatial data, however, introduced an unacceptable level of error when evaluating protection levels for small sites (*Supporting Text*). We therefore evaluated protection individually for each site, based on site-specific information and input from regional and national experts (specific sources available upon request). We assigned sites one of four levels of protection to describe their spatial overlap with protected areas: fully protected, partially protected, not protected, or unknown. We defined protection as management primarily for nature conservation, a definition that roughly corresponds to categories I–IV in the IUCN′s classification of protected areas (18).

To assess geographical patterns among sites, we used a geographic information system to assign sites to terrestrial ecoregions, biomes, biogeographic realms, islands, and mountainous areas. We defined ecoregions, biomes, and realms following Olson *et al.* (13) and mountainous areas following the Millennium Ecosystem Assessment (19). We defined islands as landmasses smaller than Greenland and used ESRI vector map data (20) to identify them.

To evaluate human pressures surrounding sites, we used a geographic information system to create buffers of 50-km radius around each site, with overlapping buffers merged to avoid double counting. We then calculated the mean human population density (www.ornl.gov/gist) and human footprint (21) within the merged buffer area (data resolution: 30 arc seconds; water bodies excluded) and compared them with the mean outside of buffers, both for the world's terrestrial surface (excluding Antarctica) and within the 338 terrestrial ecoregions (13) that contain sites.

Finally, to calculate potential annual management costs for sites, we used models developed by Balmford *et al.* (22) based on the ratio of gross national product (GNP) to country area, purchasing power parity (PPP), and site area. Data for country area, GNP, and PPP were taken from the World Bank (23). Reliable information on site area was available for only 208 of the 508 sites in developing countries, so we limited our analyses to these sites. Even for areas that are currently protected, funding is generally lower than that required to meet conservation goals (22). We therefore assumed unmet costs by using percentage estimates from Bruner *et al.* (24) (developing countries) and James *et al.* (25) (developed countries). Some sites are only partially covered by protected areas; for cost calculations, we conservatively treated these as unprotected sites.

Results and Discussion

Our criteria yield 794 trigger species, distributed among 595 sites, that are likely to become extinct unless immediate and direct

Table 1. Distribution of species facing imminent extinction (i.e., trigger species) and historically extinct species among taxa and islands, mountains, and low mainland areas

	Islands*		Mountains†		Low mainland‡		Total	
Taxon	Trigger spp.	Extinct spp.	Trigger spp.	Extinct spp.	Trigger spp.	Extinct spp.	Trigger spp.	Extinct spp.
Mammals	80	49	35	5	16	19	131	73
Birds	128	121	51	1	38	7	217	129
Reptiles§	7	8	0	0	8	1	15	9
Amphibians	88	19	268	11	52	4	408	34
Conifers	9	0	12	0	2	0	23	0
Total	312	197	366	17	116	31	794	245

Trigger species meet the criteria necessary to trigger sites for this analysis (see *Methods*). Historically extinct species are known to have become extinct since 1500 (www.iucnredlist.org) and are mapped according to their last recorded location.

*Islands are defined as landmasses smaller than Greenland (New Guinea being the largest island) and include mountainous sections of islands.

†Mountains exclude mountainous sections of islands and are defined on the mainland by using classification from the Millennium Ecosystem Assessment (19).

‡Low mainland regions are neither on islands nor in mountainous regions of continental mainlands.

§Reptiles include only taxa that have been globally assessed by the 2004 IUCN Red List: order Testudines, order Crocodylia, and family Iguanidae.

action is taken (Fig. 1; Table 2, which is published as supporting information on the PNAS web site). Since 1500, 245 extinctions have been recorded in these major taxonomic groups (www.iucnredlist.org); we therefore risk losing three times as many species as are known to have been lost in these same taxa over the last 500 years (Table 1). This result reinforces other estimates of accelerating extinction rates (1), due in part to extinctions spreading from islands containing "ecologically naïve" species (26) toward continental storehouses of terrestrial biodiversity (27). Of the 245 historically recorded extinctions, 80% occurred on islands, more than twice the proportion (39%) for trigger species (Table 1; G-test: $G_{[2]} = 972.7$, $P < 0.0001$). Accompanying this geographic expansion is a taxonomic shift: 53% of historically recorded extinctions were birds (occurring largely on islands), whereas 51% of trigger species are amphibians (28) (occurring largely in mainland mountainous areas; Table 1; G-test: $G_{[4]} = 753.0$, $P < 0.0001$). The more complete record of historical avian extinctions biases this result, but the pattern is almost certainly true because amphibians cannot disperse easily over seawater and historically did not occur on many oceanic islands.

Broader shifts in geography are also evident. For example, 21% of extinct species were found in the Neotropics (the world's richest biogeographic realm; ref. 29); this proportion has now more than doubled to 50% of trigger species (Fig. 1; G-test: $G_{[6]} = 462.0$, $P < 0.0001$), due in part to the island/mainland and taxonomic changes described above. These changes do not indicate that birds, island species, or areas outside the Neotropics are now less threatened than before. Rather, they reflect the expansion of the current extinction episode beyond sensitive species and places (e.g., exploited species and island communities) as habitat destruction and other threats intensify in the planet's most biodiverse mainland regions (30). These regions include tropical moist forests, which contain more than one-half of all sites (Fig. 2), emphasizing their well known importance for biodiversity (29). Tropical coniferous forests, meanwhile, contain the highest per-area density of sites (Fig. 2), illustrating the need for conservation action within this small, mountainous biome as well.

The 595 sites are irreplaceable targets for a global network of protected areas, but 257 (43%) currently lack any legal protection (Figs. 1 and 2). Only 203 (34%) sites are fully contained within a gazetted protected area (although management effectiveness among protected areas is uneven; ref. 31), whereas 87 (15%) are partially included in a protected area, and the protection status of 48 (8%) sites is unknown. Regardless of management status, all sites are small and, therefore, highly susceptible to human activities in the surrounding landscape. In circular buffers of 50-km radius surrounding each site, mean human population density (www.ornl.gov/gist) is 127 people/km^2 (range: 0–3,262), about three times the global mean of 45 people/km^2 and about twice the mean of 68 people/km^2 within ecoregions (13) containing sites. Similarly, mean human footprint, an aggregate index of human land use, population, and infrastructure (21), is 25.5

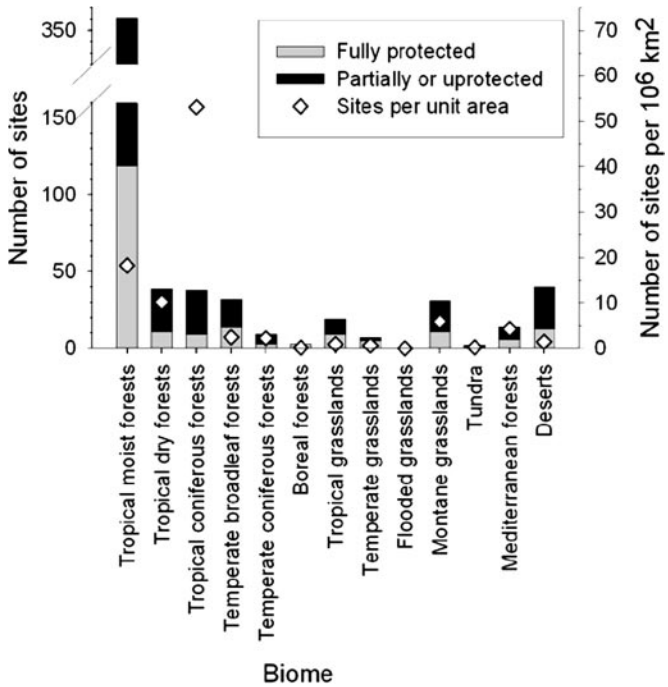

Fig. 2. Distribution of sites among 13 terrestrial biomes (13) of the world. Bars and left axis: number of sites fully included within a declared protected area (gray portions of bars) and included only partially or not at all (black portions of bars). Diamonds and right axis: number of sites per 1 million km^2. Note break in left axis.

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(range 0–46.8) within 50 km of sites compared with a global mean of 9.9 and a mean of 16.3 within ecoregions containing sites. This intensity of surrounding human activity, which is nearly identical for protected and unprotected sites, suggests that the challenges facing conservation of these highly threatened species extend beyond the small tracts of land they occupy. Their protection will require a combination of site-level activities (9) and broader-scale efforts to conserve and restore habitats, address regional threats, and maintain ecological processes (3).

Protection of these sites would conserve more than the individual threatened species that trigger them. First, 103 sites contain >1 trigger species, and several contain >5 (e.g., Massif de la Hotte, Haiti, with 13). Furthermore, sites hold many other species of conservation concern. Examining 29 Neotropical sites for which complete bird lists were available (Table 3, which is published as supporting information on the PNAS web site), we found that, in addition to the 35 trigger species occurring there, these sites support 188 restricted-range (8) and 70 globally threatened (www.iucnredlist.org) bird species that are not restricted to single sites.

Although the species we identify here require immediate attention and may often prove difficult to conserve, their recovery is within reach. Indeed, several species that would have met all three of our criteria in the past are now recovering due to successful conservation and are no longer eligible. These species include Rodrigues Fody (*Foudia flavicans*), Seychelles Warbler (*Acrocephalus sechellensis*), Seychelles Magpie-Robin (*Copyschus sechellarum*), and Black Robin (*Petroica traversi*) (www.iucnredlist.org). The 794 trigger species represent similar opportunities for conservation. Clearly, the primary response to avoid these impending extinctions will be to safeguard their sites through land purchase, conservation easements, community management, or protected area enforcement and to monitor their condition over time. In some cases, such measures will need to be complemented with control of invasive species or disease, translocation, or *ex situ* breeding or cultivation. Over the longer term, climate change may increasingly threaten trigger species, including those on isolated mountains or low-lying islands (32) (Table 1). However, although other interventions may be necessary at certain sites, protection of existing habitat is essential for all of them.

The vast majority of sites (508 of 595) are in developing countries (Table 4, which is published as supporting information on the PNAS web site) (23), and in many cases, substantial assistance from the industrialized world will be needed to pay for their conservation. After published estimates (22, 24), we calculate that annual management costs per site in developing countries will likely span four orders of magnitude, from $470 to $3,500,000 (median $220,000). Annual costs for each of three sites in Ecuador, for example, average $36,000 (managed by Fundación Jocotoco; R.R., unpublished data). One-time acquisition costs for unprotected sites can be many times their management costs (25) but may often be much lower because protection may be achieved through redesignation of public lands to higher levels of protection or better enforcement of existing designations (24).

The species identified here are only a fraction of those at risk of extinction from intensifying human activities. Available data limited our analyses to five taxonomic groups, and more trigger species (particularly freshwater species, terrestrial invertebrates, and plants) will be identified as knowledge improves. Even within the analyzed taxa, species not confined to a single site can be equally threatened and in need of conservation actions (e.g., wide-ranging but fast-declining species, such as Asian *Gyps* vultures; ref. 33). Furthermore, a global conservation strategy must also consider broader biodiverse regions, population diversity, ecological processes, and ecosystem services to human communities (3, 5–8, 34, 35) (*Supporting Text*). Nonetheless, the sites we identify are a critical subset of global conservation priorities, complementing other efforts by focusing on relatively small scales and short time horizons: They are known places where extinctions are imminent unless immediate conservation action is taken.

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