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Conservation Imperatives: securing the last unprotected terrestrial sites harboring irreplaceable biodiversity

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Abstract

Ambitious biodiversity goals to protect 30% or more of the Earth's surface by 2030 (30x30) require strategic near-term targets. To define areas that must be protected to prevent the most likely and imminent extinctions, we propose Conservation Imperatives—16,825 unprotected sites spanning ~164 Mha of the terrestrial realm that harbor rare and threatened species. We estimate that protecting the Conservation Imperatives would cost approximately US$169 billion (90% probability: US$146—US$228 billion). Globally, 38% of the 16,825 sites are either adjacent to or within 2.5 km of an existing protected area, potentially reducing land acquisition and management costs. These sites should be prioritized for conservation action over the next 5 years as part of a broader strategy to expand the global protected area network. The expansion of global protected areas between 2018 and 2023 incorporated only 7% of sites harboring range-limited and threatened species, highlighting a renewed urgency to conserve these habitats. Permanently protecting only 0.74% of land found in the tropics, where Conservation Imperatives are concentrated, could prevent the majority of predicted near-term extinctions once adequately resourced. We estimate this cost to be from US$29 billion to US$46 billion per year over the next 5 years. Multiple approaches will be required to meet long-term protection goals:

providing rights and titles to Indigenous Peoples and Local Communities (IPLCs) conserving traditional lands, government designation of new protected areas on federal and state lands, and land purchase or long-term leasing of privately held lands.

KEYWORDS

Conservation Imperatives, 30x30, protected area targets, rare species, land cover fraction mapping, geospatial analysis, land costs analysis

Key points

- There is an urgent need to prioritize the conservation of habitats of rare and threatened species as part of a larger global biodiversity strategy.
- Conservation Imperatives offer a solution to conserving the last unprotected sites harboring rare, range-restricted, and threatened species and should be a central component of the ambitious goals to protect at least 30% of the Earth's surface by 2030.
- The Conservation Imperatives identified in this study are highly concentrated, requiring only ~164 Mha globally to avoid extinctions; this equates to only 1.22% of the Earth's entire terrestrial surface and 0.74% of land in the tropics.
- Targeted investments to prevent extinctions in parallel with the conservation of carbon-rich regions are necessary as the world sets about expanding the protected area network from 15.7% today to 30% by 2030.
- Conserving Conservation Imperatives is achievable and affordable, especially in the tropics, as the purchase of the tropical subset of Conservation Imperatives costs about US$169 billion (90% probability: US$146–US$228 billion), or US$34 billion (90% probability: US$29.2–US $45.6 billion) per year over 5 years.
- As Conservation Imperatives represent the most biologically important and threatened places to protect, they can be thought of as "anchor points" to design regional-scale conservation planning efforts under 30×30.

Introduction

In late December 2022, at the United Nations Convention on Biological Diversity's 15th Conference of Parties (COP15), more than 190 parties adopted the 30×30 target—to protect at least 30% of the world's lands, oceans, and inland waters by 2030 (1). Conservation biologists, Indigenous Peoples, science-based NGOs, corporate leaders, and others have endorsed the 30×30 target and also called for protecting half of the terrestrial realm for humanity to have the best chance to reverse biodiversity loss, stabilize Earth's climate, prevent ecosystem collapse, and avoid future pandemics (2–5). Either goal—30% protected or 50% protected—will encourage the protection of large areas of land to meet targets, but this strategy can easily result in an underrepresentation of biodiversity (6). Land protection targets must account for the urgency of preventing numerous species extinctions and extirpations of small, rare, and range-restricted populations.

The purpose of this paper is to offer a science-based strategy to secure and protect the remaining homes of rare and endangered species through timely, affordable investments in land acquisition and habitat conservation. To this end, we introduce the term Conservation Imperatives, defined as currently unprotected sites that contain rare, threatened, and narrow-range endemic species. Specifically, our approach is to map unprotected sites harboring rare species while accounting for converted habitats and estimating costs to put these lands under conservation stewardship. We also seek to determine progress in the protection of global sites of rarity as determined from 2018 to 2023. Finally, we outline new efforts to leverage Conservation Imperatives to finance protection where immediate focus is needed and create anchor points for wider conservation planning under a global 5-year strategy.

Advancing Conservation Imperatives is a global prioritization scheme in the sense that preventing extinctions is proposed as an immediate conservation target. We strive for maximum buy-in by all nations, Indigenous groups, and local communities who have jurisdiction over such lands to preserve opportunities for expanding protection to Conservation Imperatives. We intentionally avoid prioritizing sites on a global scale. The maps and data we present here should be used as a starting point for subsequent ecoregion-based or regional prioritizations within each realm. A rich literature on systematic conservation planning and reserve design can inform methodologies for evaluating and delineating proposed sites at the regional level (7–10). Local teams of experts in each country can also take advantage of higher-resolution spatial data—for species distributions, population viability of threatened species, representation of rare habitats, land cover, extent of degraded lands, restoration potential, connectivity options, threats from development, extensive records of land purchase or leasing prices, and feasibility of conservation effort—often unavailable in global assessments. These essential planning efforts reinforce local ownership of Conservation Imperatives and will help reduce extinction risk by considering the likely future conditions in each region.

Methods

Species rarity layer

We combined six widely used data layers employed in published global biodiversity assessments to identify sites supporting rare, narrow-range endemic, and endangered species (4). Using the latest dataset of global protected areas (11) as our base map, we sequentially intersected polygons identified as supporting rare and threatened species to avoid double counting of the overlapped areas. These include Alliance for Zero Extinction (AZE) sites, the range-restricted rarity of forest species, the International Union for Conservation of Nature (IUCN) Red List, Key Biodiversity Areas (KBAs), a second estimator of range-restricted rarity among vertebrates, and range-restricted vascular plants. For more details on the construction of the species rarity layer, see Dinerstein et al. (4) (Presentation 1: Supplementary Table 1). The total extent of these six data layers, minus the area covered by global protected areas, determines the remaining unprotected segment, which defines the extent of the Conservation Imperatives (Figure 1). This layer of species rarity was then refined using the fractional land cover analysis described below.

For freshwater species, which are on average more endangered than terrestrial species, we relied on the same data layers for the following reasons: i) the life histories of some of the most endangered vertebrates in the IUCN Red List of Endangered Species (Layer 3, see Figure 1) could be considered freshwater or at least freshwater-dependent rather than terrestrial species. These taxa include amphibians and some reptile groups; ii) the IUCN Red List polygons (Layer 3) also contain the spatial distributions of several relatively well-studied freshwater taxa for which range maps exist. These include freshwater turtles, freshwater fish, freshwater crabs, freshwater mollusks, freshwater crayfishes and shrimps, odonates (dragonflies and damselflies), and some aquatic plants; and iii) more than half of all endangered vertebrates in the Alliance for Zero Extinction layer (Layer 1) are amphibians.

Fractional land cover analysis

We introduced a fractional land cover analysis to derive a more accurate estimate of the true Area of Habitat (hereafter "AoH") for rare and threatened species because published range data contain varying amounts of agricultural, pastoral, and urban lands. The uneven resolution of the most widely used global biodiversity layers, coupled with rapid land-use change from conversion to agriculture and urbanization, results in many species rarity sites now containing areas of non-habitat. To identify and remove non-habitat, we used Copernicus Global Land Cover Layers CGLS-LC100 Collection 3 at 100 m resolution (12) (hereafter "Copernicus data") and Google Earth Engine (13) to generate a land cover map that includes fractions of all land cover types occurring in a pixel at 100 m resolution.

We used seven classes to create the fractional layer: Forest, Shrub, Grass, Crop, Urban, Bare Ground, and Permanent Water (inland water bodies). We defined Forest using the percent tree cover in the Copernicus data that varied by biome and set cutoff levels based on expert knowledge in each biome and their distinguishing ecological characteristics. Forest is defined as pixels with a tree cover fraction > 80% for the tropical forest biome, > 50% for the temperate forest biome, and > 30% for the boreal forest and mangrove biomes. To differentiate desert habitat from bare ground in the desert and xeric shrub biome, desert is defined as > 70% bare soil and bare ground as 50–69% bare soil in this biome. For all other cover types, we did not differentiate the percent cover among biomes. Shrub cover is defined as pixels with a shrub cover fraction ≥ 30%; Grass as a grass cover fraction ≥ 50%; Bare Ground as a bare cover fraction ≥ 50%; Urban as an urban cover fraction ≥ 10%; Permanent Water (inland) as a permanent water cover fraction ≥ 30%; and Crop as a cropland cover fraction >1% (to avoid any potential cultivated areas).

The species rarity layer and the fractional land cover map were overlaid to calculate the contribution of different cover types to unprotected polygons (Figure 1). To calculate the AoH (14) in species rarity sites, we masked all land in the Crop, Urban, and Bare Ground cover types. We recognize that crops and bare ground can represent suitable habitats for some species that are threatened or have restricted ranges. Evaluating these individual species' requirements is, however, beyond the scope of this global assessment. In instances where the fractional land cover analysis resulted in small, isolated fragments of rare species habitat surrounded by developed or cultivated land, fragments smaller than 1 ha were removed due to high near-term conversion risk. Finally, we overlaid the resulting species rarity layer with the world's 846 terrestrial ecoregion boundaries to be able to categorize Conservation Imperatives by ecoregion (15). The result of these sequential overlays allows us to identify Conservation Imperatives (Figure 1).

Adjacency analysis

To determine the adjacency of Conservation Imperatives to existing reserves mapped in the World Database on Protected Areas (WDPA) layer (Figure 1), we buffered protected areas by 2.5 km and assessed which sites fell within this buffer. For this exercise, we assumed that site protection and management could be easier than the expansion of existing protected areas or corridor establishment. We chose 2.5 km as the upper limit based on the minimum corridor width recommended for the largest terrestrial vertebrates (elephants) to move between isolated patches of habitat (16).

Cost assessment

Establishing accurate spatial delineation of Conservation Imperatives sets the stage for estimating the expected costs of protected area designation. Previous assessments of costs for conservation at the global scale have relied on extrapolation of land values based on agricultural and pastoral potential (17, 18).

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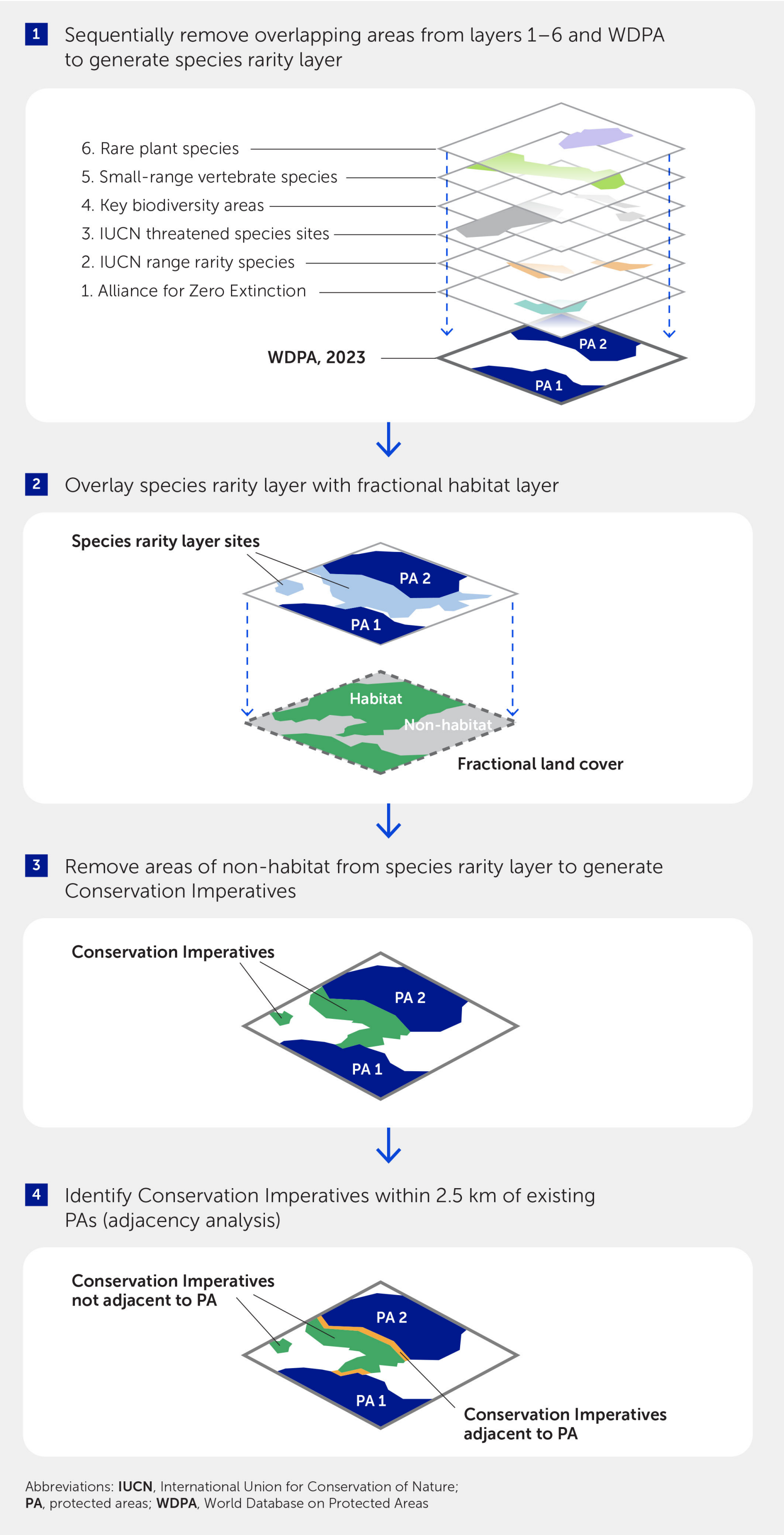

FIGURE 1
Schematic illustrating the construction of Conservation Imperatives and adjacency analysis. 1) Six layers of rare species data were overlaid together with the World Database on Protected Areas (11) to remove overlapping areas and generate the species rarity layer. 2) The resulting species rarity layer was overlaid on a fractional land cover map with areas of habitat and non-habitat. 3) Areas of non-habitat were removed from the species rarity layer to derive Conservation Imperatives. 4) After completion of the previous steps, spatial analysis was performed to identify Conservation Imperatives that are adjacent to an existing reserve (i.e., within 2.5 km).

Despite recent calls for datasets reflecting the real costs of land for conservation (19, 20), comprehensive datasets remain unavailable. Complicating this estimation is that multiple stewardship mechanisms with different cost implications—such as private land purchase, leasing of community reserves and forests, re-establishing Indigenous land rights, and government re-designations—affect the true total costs of protecting sites harboring rare species. Using actual data on costs to place land under conservation stewardship can provide a clearer approximation of the resources required to secure critical sites for biodiversity (19).

To estimate the cost of securing Conservation Imperative sites in the tropical belt, we collected empirical data from land protection projects occurring between 2008 and 2022, fit generalized linear regression models, and applied a simulation approach. Our dataset consisted of 1,016 projects compiled from IUCN Netherlands, the Quick Response Fund for Nature, and World Land Trust (21), supplemented by unpublished data from other NGOs focused on land purchases that met our criteria for inclusion. These organizations regularly fund land acquisition, designation, and protection projects globally, with a higher concentration in the tropics. This portfolio includes a range of projects, including the expansion of existing parks and community reserves, establishment of privately protected areas, and creation of community forest reserves. Acquisition costs cover the purchase price and legal and notary fees, which were as much as 10% of the acquisition cost. For leased land projects of varying lengths, we calculated an annual value and then extrapolated the cost per hectare for 10 years—the dataset's median lease length. We adjusted all costs to 2023 US$ to account for inflation. We removed projects with incomplete information on location, purchase cost, purchase size, and lease length. After cleaning the dataset, the remaining locations contained 833 sites distributed across all 6 major realms and 14 biomes (Presentation 1: Supplementary Figure 1).

We next fit linear regression models to the empirical cost per hectare of land protection projects. We used a log transformation on cost-per-hectare values to reduce skew and create an approximate normal distribution. We hypothesized that land value could be influenced by the biogeographical realm, region, ecoregion, area of land being secured, type of land acquisition, and country-level economic factors (4, 22). We used the following covariates as predictors: realm, size of acquisition, type of acquisition (categorized into purchase or lease), national per capita GDP, and country population size (23). All continuous covariates were scaled and centered for interpretation. The mean per capita GDP and population were extracted based on the country in which the project occurred between 2010 and 2020. A random effect for data source was added to account for possible variation among the groups that supplied project data. We fit candidate models and used the Akaike Information Criterion and conditional R^2 values to select the most informative model for land value [MuMin R Package (24)]. We tested for correlations among continuous covariates and excluded variables with $R > 0.65$ values prior to the analysis (5). We also tested for multiple collinearity using the variance inflation factor (25). Neither test required the removal of covariates.

To calculate the price to place Conservation Imperatives under conservation stewardship, we used Monte Carlo simulations (26) to estimate the cost per hectare and total land value of all sites under simulated purchase scenarios. Each simulation used the land value model to predict the cost per hectare of each Conservation Imperative site using random values for acquisition size (assuming multiple smaller purchases would be needed to secure large sites), acquisition type (assuming a mix of purchase and lease), and data source and determined land value by multiplying the predicted cost per hectare by the known size of the site. We ran 10,000 simulations with random values drawn from distributions parameterized by realm. Total cost estimates were calculated as the mean across all simulations, and we used 90% probability distributions to measure uncertainty. We used this approach to determine the total cost of placing all Conservation Imperatives in the tropical belt under conservation stewardship. We then identified the top 10 ecoregions in each realm harboring the most Conservation Imperatives and assessed the price of conserving those sites by ecoregion. We converted all results to US$ per square kilometer to keep units comparable to the fractional analysis. The code used for model fitting and simulation can be found in the Supplementary Materials.

Representation of species rarity among newly created protected areas

To determine if the increases in the global protected area estate over the last 5 years have effectively addressed rare and endemic species exposed to the greatest risks of extinction, we intersected the Conservation Imperatives polygons with the most recent map of the WDPA using protected area categories 1–7 (April 2023) (11). We predicted that new reserves created from 2018 to 2023 would cover > 50% of the Conservation Imperatives.

Results

Fractional land cover analysis

We identified 16,825 sites harboring rare and threatened species, covering ~164 Mha or 1.22% of the Earth's land surface (Figure 2). This AoH represents a 46% reduction from earlier estimates based on a published compilation of identified areas of importance for rare and threatened species [e.g., KBAs, Red List sites (4)]. Most of these reductions occurred in large blocks of unprotected habitat rather than in smaller fragments.

Reduction in total AoH harboring unprotected rarity differed by latitude and by biome. In the four major tropical realms, we found a 45% reduction in total land area. In the non-tropical realms, we estimated a 49% reduction in area (Table 1). Within biomes that comprise the tropical realms, tropical and subtropical dry broadleaf forests underwent the largest reduction in target habitat (77%), followed by tropical and subtropical coniferous forests (58%). Tropical and subtropical moist broadleaf forests, which contained the highest concentration (75%) of Conservation Imperatives, showed a 49% reduction in area (Figure 3; Table 2).

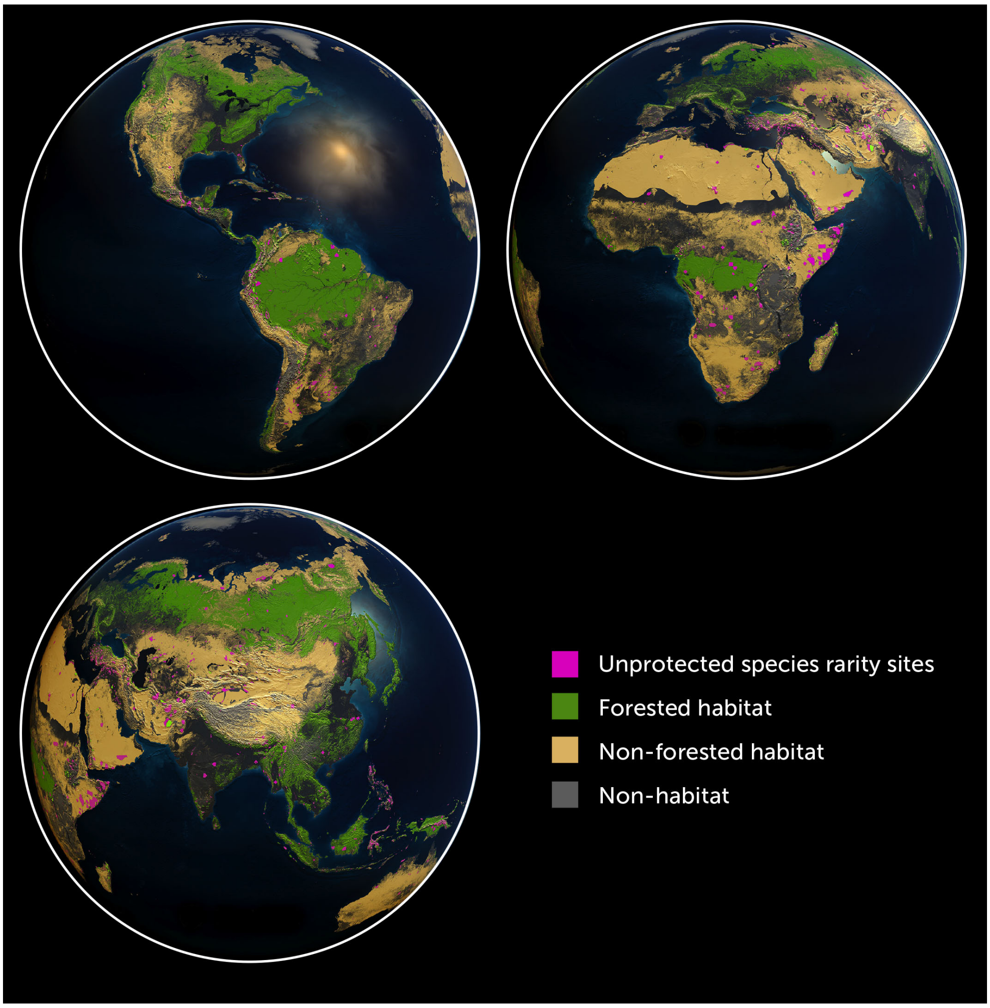

FIGURE 2
Map of global unprotected species rarity site. Global distribution of the unprotected species rarity sites (magenta area) across predominantly forested habitat (green) and non-forested habitat (yellow), with non-habitat areas (grey) removed from previously designated species rarity sites, covering 1.22%. Non-habitat areas include land classified as urban, agricultural, and degraded.

TABLE 1 Extent of habitat by biogeographic realm after applying fractional land cover to species rarity sites and removing non-habitat area.

Biogeographic realm	Forested habitat (km^2)	Non-forested habitat (km^2)	Total habitat (km^2)	Habitat reduction (%)*
Afrotropic	65,301	350,050	415,351	32
Australasia	180,550	37,066	217,616	36
Indomalayan	150,262	4,662	154,924	56
Nearctic	17,512	23,501	41,012	49
Neotropic	174,945	137,045	311,990	54
Oceania	1,766	241	2,007	84
Palearctic	73,220	423,791	497,010	49
Total	**663,556**	**976,355**	**1,639,911**	**46**

*Approximate reduction of unprotected rare and threatened species areas from 2019 levels versus total area extent from newly compiled data sets.

Conservation Imperatives

Conservation Imperatives are highly concentrated. We found a distinct skew in the distribution of the 16,825 sites harboring unprotected rarity across biogeographic realms and biomes (Figure 2; Tables 3, 4; Presentation 1: Supplementary Table 2). The majority of unprotected sites fall within the tropical and subtropical moist forests biome. Within the same biome but sorted by realm, the Neotropics had the most sites (38% of all Conservation Imperatives), followed by the Indomalayan (34%), Australasia (18%), and Afrotropic (9%) realms. Sites were also clustered within realms. The 10 ecoregions with the most Conservation Imperatives within the four major tropical realms account for 63.5% of all sites globally (Figure 4; Table 5). The top five countries in the world with the highest number of Conservation Imperatives are the Philippines, Brazil, Indonesia, Madagascar, and Colombia, and together they account for 59% of all sites globally. Over 87% of all Conservation Imperatives occur in just 30 countries (Table 6).

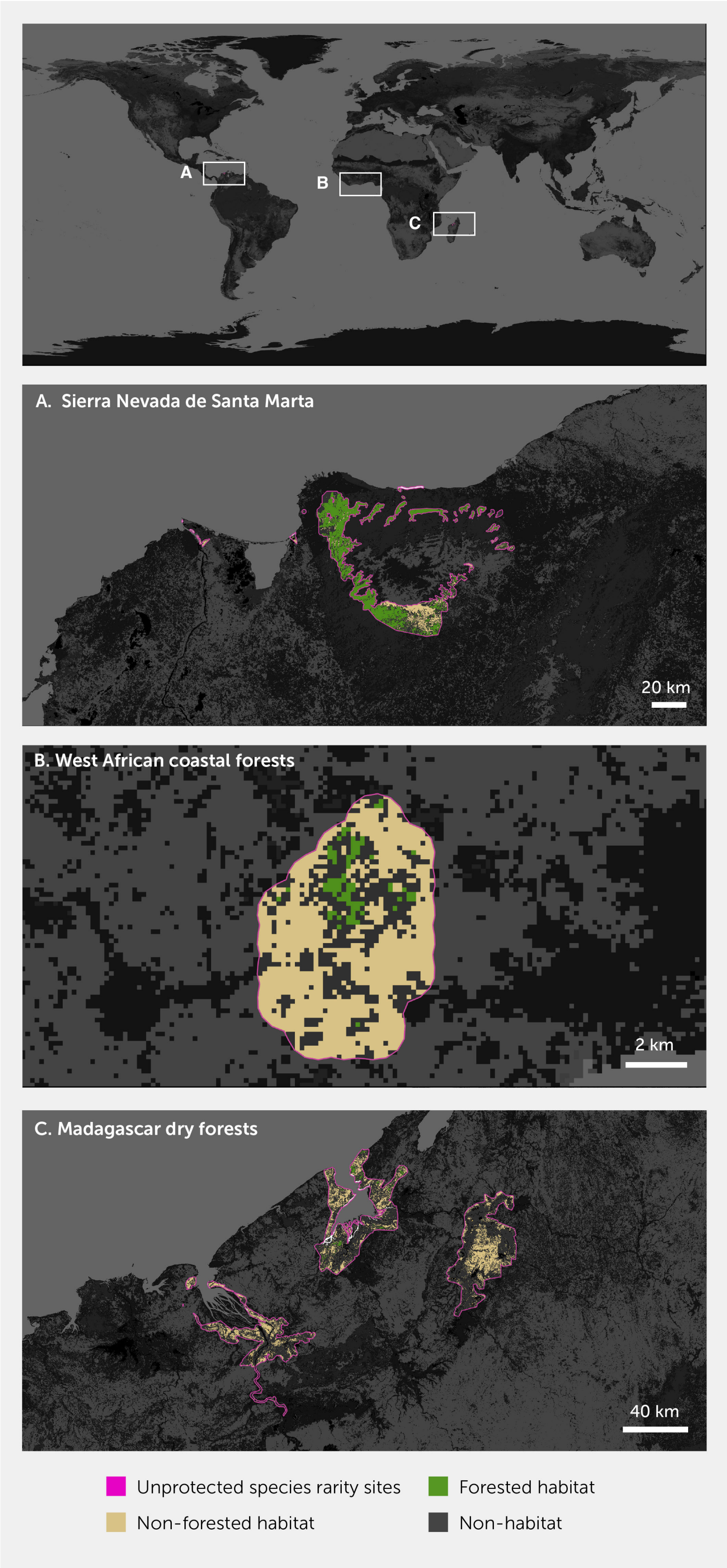

FIGURE 3
Effect of fractional analysis when identifying and removing non-habitat (Other) areas from species rarity polygons in several regions with high species rarity. Forested and non-forested habitats are retained. **(A)** Sierra Nevada de Santa Marta, Colombia; **(B)** West African coastal forests; and **(C)** Madagascar dry forests.

TABLE 2 Extent of habitat by biome after applying fractional land cover to species rarity sites and removing non-habitat area.

No.	Biome name	Forested habitat (km^2)	Non-forested habitat (km^2)	Total habitat (km^2)	Habitat reduction (%)*
1	Tropical/subtropical moist broadleaf forests	536,606	55,436	592,043	49
2	Tropical/subtropical dry broadleaf forests	7,903	13,248	21,152	77
3	Tropical/subtropical coniferous forests	13,152	3,073	16,225	58
4	Temperate broadleaf/mixed forests	28,563	25,156	53,719	68
5	Temperate conifer forests	19,777	8,481	28,257	33
6	Boreal forests/taiga	51,147	35,018	86,165	22
7	Tropical/subtropical grasslands, savannas, shrublands	17	370,057	370,075	14
8	Temperate grasslands, savannas, shrublands	5	82,146	82,151	53
9	Flooded grasslands, savannas	2	8,794	8,796	65
10	Montane grasslands, shrublands	41	32,775	32,816	62
11	Tundra	1	45,632	45,633	35
12	Mediterranean forests, woodlands, scrub	5	36,162	36,167	78
13	Deserts, xeric shrublands	7	259,015	259,022	46
14	Mangroves	6,329	1,361	7,690	44
	Total	**663,556**	**976,355**	**1,639,911**	**46**

*Approximate reduction of unprotected rare and threatened species areas from 2019 levels versus total area extent from newly compiled data sets.

Representation of species rarity among newly created protected areas

We predicted that >50% of new protected areas designated between 2018 and 2023 would overlap with unprotected species rarity sites. We estimated that 1.2 million km^2 was added to the global protected area estate over this 5-year time period (11). Of that, the largest extent was located in two ecoregions (#473 Japura-Solimões-Negro Moist Forests and #831 North Arabian Desert, totaling 192,000 km^2), but based on our analysis these additions showed very little overlap with areas harboring rare and threatened species. In fact, over this same time period, only 109,779 km^2, or less than 7% of identified Conservation Imperatives, have been added to the World Database on Protected Areas (Figure 5), leaving the vast majority of these sites at risk of conversion and degradation. Expressed slightly differently, had the 1.2 million km^2 set aside during the 2018–2023 period included only Conservation Imperatives, 73% of these sites globally would now be under protection.

TABLE 3 Distribution of Conservation Imperative sites (2023) by realm.

Biogeographic realm	Forest (km^2)	Grass (km^2)	Shrub (km^2)	Desert (km^2)	Total (km^2)	Number of sites	Total sites (%)
Afrotropic	65,301	124,904	224,425	722	415,351	1,870	11.1
Australasia	180,550	30,538	6,210	318	217,616	2,526	15.0
Indomalayan	150,262	2,681	1,963	18	154,924	4,569	27.2
Nearctic	17,512	11,355	11,914	233	41,012	184	1.1
Neotropic	174,945	89,346	47,455	244	311,990	5,972	35.5
Oceania	1,766	149	92	-	2,007	52	0.3
Palearctic	73,220	262,573	20,868	140,349	497,010	1,652	9.8
Total	**663,556**	**521,545**	**312,927**	**141,883**	**1,639,911**	**16,825**	**100**

The four tropical realms account for 89% of all sites globally.

TABLE 4 Distribution of Conservation Imperative sites in each biome (2023).

No.	Biome name	Forest (km^2)	Grass (km^2)	Shrub (km^2)	Desert (km^2)	Total (km^2)	Number of sites	Total sites (%)
1	Tropical/subtropical moist broadleaf forests	536,606	27,081	28,355	–	592,043	12,580	74.8
2	Tropical/subtropical dry broadleaf forests	7,903	5,925	7,323	–	21,152	554	3.3
3	Tropical/subtropical coniferous forests	13,152	552	2,521	–	16,225	170	1.0
4	Temperate broadleaf, mixed forests	28,563	24,055	1,101	–	53,719	503	3.0
5	Temperate conifer forests	19,777	7,860	620	–	28,257	125	0.7
6	Boreal forests, taiga	51,147	25,828	9,191	–	86,165	88	0.5
7	Tropical/subtropical grasslands, savannas, shrublands	17	165,980	204,077	–	370,075	562	3.3
8	Temperate grasslands, savannas, shrublands	5	63,503	18,643	–	82,151	439	2.6
9	Flooded grasslands, savannas	2	8,435	358	–	8,796	57	0.3
10	Montane grasslands, shrublands	41	29,993	2,782	–	32,816	428	2.5
11	Tundra	1	43,136	2,497	–	45,633	37	0.2
12	Mediterranean forests, Woodlands, scrub	5	21,619	14,543	–	36,167	436	2.6
13	Deserts, xeric shrublands	7	96,743	20,389	141,883	259,022	619	3.7
14	Mangroves	6,329	835	526	–	7,690	227	1.3
	Total	**663,556**	**521,545**	**312,927**	**141,883**	**1,639,911**	**16,825**	**100**

The tropical and subtropical moist broadleaf forests biome alone accounts for three-quarters of all sites globally.

Cost analysis

The model of land acquisition costs per hectare that included realm, purchase type, purchase size, per capita GDP, and population size performed best and had an R^2 value of 0.76 (Presentation 1: Supplementary Table 4). Among the variables we tested, acquisition size [-0.67, 95% CI (-0.71, -0.64); larger acquisitions had lower per-ha costs], acquisition type [0.97, 95% CI (0.66, 1.28); purchases were more expensive than leases], and realm were the most useful predictors and explained much of the model variation on their own. We also found that higher per capita GDP [0.18, 95% CI (0.07, 0.28)] and human population density [0.03, 95% CI (0.02, 0.08)] increased land prices (Presentation 1: Supplementary Table 4).

In Monte Carlo simulations of the land cost for Conservation Imperatives, we found that the total cost of the Conservation Imperatives in the tropics is US$169 billion, with a 90% probability between US$146 and US$228 billion (Presentation 1: Supplementary Figure 2). Much of this uncertainty appeared to come from variations in the size and type (purchases and leases) of land acquisitions. Land acquisition was least expensive in Australasia and most expensive in the Indomalayan realm but somewhat similar in the other realms (Table 7, Presentation 1: Supplementary Figure 2B). The Afrotropic, Indomalayan, and Neotropic realms showed the largest variation in predicted total cost, which appeared to arise from larger cost differences between lease arrangements and purchases and the number of sites that were either leased or purchased in each simulation (Presentation 1: Supplementary Figure 2). Land costs for the top 10 ecoregions—ranked by number of species rarity sites—from each of the four major tropical realms would be US$59.4 billion (90% probability of US$29–US$108 billion), safeguarding 63% of all sites (Figure 4; Table 5). To cover Conservation Imperatives at all latitudes, the total cost increases to US$263 billion (90% probability of US$204–US$339 billion).

Adjacency analysis

Adjacency analysis of Conservation Imperative sites relative to existing protected areas revealed that 38% (SD = 36.01) of the 16,825 sites either bordered or were within 2.5 km of a nearby existing protected area (Table 6). The five countries with the most Conservation Imperatives had at least 20% adjacency to existing protected areas (Presentation 1: Supplementary Figure 3). Colombia ranked highest among the top 30 countries with 56% of all Conservation Imperatives bordering protected areas.

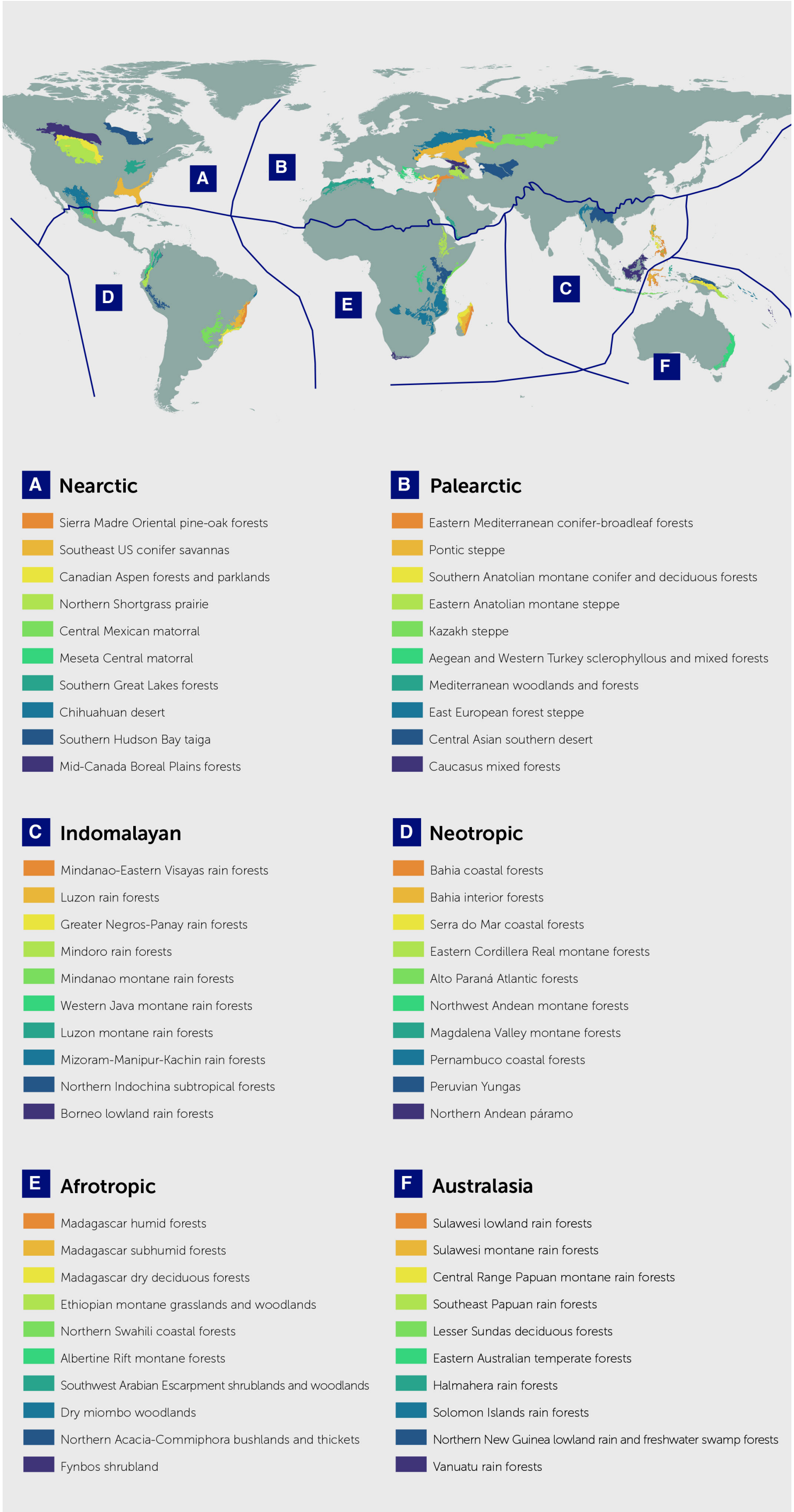

FIGURE 4
The 10 ecoregions in each realm containing the highest number of Conservation Imperatives.

TABLE 5 The top 10 ecoregions in each realm with the highest number of Conservation Imperative sites (2023) and the total remaining natural habitat and estimated cost to place under conservation stewardship.

ID	Ecoregion name	Total habitat area (km^2)	Number of sites	% of sites in realm	Estimated cost (million US$)		
					Mean	Lower 90% CI	Upper 90% CI
Afrotropic							
17	Madagascar humid forests	4,295	614	32	337	190	539
18	Madagascar subhumid forests	3,836	250	13	302	164	477
32	Madagascar dry deciduous forests	3,025	59	3	241	120	398
79	Ethiopian montane grasslands and woodlands	725	49	3	56	24	103
25	Northern Swahili coastal forests	16,190	48	3	1,201	447	2,259
1	Albertine Rift montane forests	5,200	43	2	352	111	713
108	Southwest Arabian Escarpment shrublands and woodlands	2,407	38	2	272	133	462
42	Dry miombo woodlands	376	35	2	26	10	50
51	Northern Acacia-Commiphora bushlands and thickets	10,976	32	2	710	179	1,545
89	Fynbos shrubland	2,049	29	2	221	64	472
				Total cost of top 10 ecoregions	3,717		
Australasia							
156	Sulawesi lowland rain forests	25,417	1,090	45	197	136	276
157	Sulawesi montane rain forests	36,785	421	18	270	152	428
139	Central Range Papuan montane rain forests	39,150	379	16	231	83	441
153	Southeast Papuan rain forests	15,727	46	2	98	37	184
163	Lesser Sundas deciduous forests	1,916	41	2	15	9	22
168	Eastern Australian temperate forests	2,192	39	2	31	19	45
140	Halmahera rain forests	3,147	32	1	24	16	35
152	Solomon Islands rain forests	10,456	25	1	69	46	97
148	Northern New Guinea lowland rain and freshwater swamp forests	6,101	22	1	39	18	69
159	Vanuatu rain forests	992	18	1	7	5	10
				Total cost of top 10 ecoregions	980		
Indomalayan							
247	Mindanao-Eastern Visayas rain forests	22,648	1,561	36	14,948	9,354	22,070
241	Luzon rain forests	15,139	1,123	26	9,912	6,336	14,223
231	Greater Negros-Panay rain forests	1,813	190	4	1,184	672	1,819
248	Mindoro rain forests	1,663	178	4	971	501	1,664
246	Mindanao montane rain forests	7,517	139	3	4,880	2,411	8,015
288	Western Java montane rain forests	709	100	2	467	239	765
240	Luzon montane rain forests	2,644	57	1	1,732	752	2,975
249	Mizoram-Manipur-Kachin rain forests	5,395	52	1	3,037	1,796	4,651
256	Northern Indochina subtropical forests	3,171	44	1	2,097	1,174	3,205
219	Borneo lowland rain forests	13,993	43	1	8,399	2,961	16,403
				Total cost of top 10 ecoregions	47,628		

(Continued)

TABLE 5 Continued

ID	Ecoregion name	Total habitat area (km^2)	Number of sites	% of sites in realm	Estimated cost (million US$)		
					Mean	Lower 90% CI	Upper 90% CI
Nearctic							
327	Sierra Madre Oriental pine-oak forests	1,828	16	9	76	47	112
399	Southeast US conifer savannas	1,149	15	8	66	35	107
386	Canadian Aspen forests and parklands	121	9	5	7	4	12
396	Northern Shortgrass prairie	672	9	5	40	21	64
427	Central Mexican matorral	603	8	4	21	7	41
432	Meseta Central matorral	819	8	4	31	15	55
342	Southern Great Lakes forests	222	7	4	11	4	22
428	Chihuahuan desert	3,490	7	4	131	55	241
382	Southern Hudson Bay taiga	1,782	6	3	99	42	177
376	Mid-Canada Boreal Plains forests	561	5	3	30	12	55
				Total cost of top 10 ecoregions	513		
Neotropic							
442	Bahia coastal forests	3,563	1,635	27	410	307	543
443	Bahia interior forests	1,161	579	10	138	107	174
500	Serra do Mar coastal forests	3,134	434	7	372	277	481
460	Eastern Cordillera Real montane forests	18,176	279	5	1,796	1,201	2,541
439	Alto Paraná Atlantic forests	2,177	192	3	241	162	338
486	Northwest Andean montane forests	18,454	192	3	1,888	1,169	2,775
477	Magdalena Valley montane forests	9,685	156	3	927	516	1,511
491	Pernambuco coastal forests	160	150	2	19	13	26
493	Peruvian Yungas	11,658	142	2	1,191	852	1,600
593	Northern Andean páramo	892	121	2	92	66	125
				Total cost of top 10 ecoregions	7,075		
Palearctic							
791	Eastern Mediterranean conifer-broadleaf forests	6,900	114	7	1,092	634	1,681
735	Pontic steppe	9,506	101	6	1,675	1,017	2,497
804	Southern Anatolian montane conifer and deciduous forests	12,680	70	4	2,255	1,241	3,512
727	Eastern Anatolian montane steppe	9,761	57	3	1,501	757	2,492
732	Kazakh steppe	9,220	53	3	1,504	845	2,375
785	Aegean and Western Turkey sclerophyllous and mixed forests	1,577	43	2	270	143	437
798	Mediterranean woodlands and forests	2,221	40	2	295	137	511
661	East European forest steppe	2,191	39	2	382	210	608
819	Central Asian southern desert	3,436	37	2	486	269	780
650	Caucasus mixed forests	5,851	36	2	901	488	1,431
				Total cost of top 10 ecoregions	10,361		

This includes tropical and non-tropical ecoregions.

TABLE 6 Top 30 countries with the highest number of Conservation Imperative sites, their percentage total, median and total area of sites (km^2), and the number and percentage of sites within each country that are adjacent to existing protected areas (i.e., within 2.5 km of boundary).

Country	Number of Conservation Imperative sites	% of total sites	Median area of sites (km^2)	Total area of sites (km^2)	Number of sites adjacent to an existing protected area (within 2.5 km of boundary)	% of sites adjacent to an existing protected area in country
Philippines	3,355	19.5	0.46	53,816	833	25
Brazil	3,342	19.4	0.31	35,632	781	23
Indonesia	1,893	11.0	0.50	116,773	387	20
Madagascar	968	5.6	0.37	14,585	183	19
Colombia	761	4.4	0.93	39,827	423	56
Ecuador	653	3.8	0.38	35,026	157	24
Papua New Guinea	527	3.1	0.36	81,800	26	5
India	437	2.5	5.23	20,861	65	15
Peru	342	2.0	13.42	43,590	101	30
Turkey	304	1.8	28.53	50,166	2	1
Russia	291	1.7	54.48	138,436	89	31
China	276	1.6	22.68	41,276	47	17
Mexico	230	1.3	17.22	33,441	63	27
Argentina	187	1.1	40.87	61,285	38	20
Australia	137	0.8	2.31	35,705	54	39
United Republic of Tanzania	127	0.7	0.24	1,041	52	41
South Africa	116	0.7	9.74	40,648	52	45
Myanmar	114	0.7	16.78	22,883	16	14
Ethiopia	109	0.6	0.86	40,513	6	6
Kazakhstan	104	0.6	85.39	58,230	19	18
United States of America	102	0.6	17.78	10,636	51	50
Venezuela	93	0.5	1.77	2,793	50	54
Kenya	92	0.5	0.69	16,297	22	24
Vietnam	85	0.5	5.47	3,274	42	49
Bolivia	81	0.5	16.31	8,612	27	33
Yemen	78	0.5	27.00	6,111	1	1
Malaysia	76	0.4	7.88	9,141	25	33
Democratic Republic of the Congo	73	0.4	13.46	49,350	23	32
Syria	70	0.4	5.16	2,360	1	1
Chile	66	0.4	3.49	2,652	22	33
Total of top 30 countries	**15,089**	**87.6**		**1,076,759**	**3,658**	**24**

Discussion

Key findings

Five key insights emerging from this study highlight the need to prioritize the conservation of rare and threatened species and their habitats as an urgent near-term target within a larger global biodiversity strategy: i) Conservation Imperatives identified in this study represent a mere 1.2% of the Earth's terrestrial surface (0.74% in the tropical belt); ii) Conservation Imperatives were underrepresented in the creation of new protected areas over the last 5 years, indicating that a focus on species rarity is necessary; iii) if new protected areas created from 2018 to 2023 had been more strategically located to cover polygons identified as Conservation Imperatives, 73% of them could have been protected; iv) the bulk of the world's rare and endangered species could be represented in protected areas for approximately US$25 billion/year for 5 years, and for only US$5 billion/year for 5 years in the Neotropics, where ecoregions contain the largest number of Conservation Imperatives; and v) the proximity of 38% of the 16,825 Conservation Imperatives to existing protected areas could greatly reduce barriers to protection and the costs of subsequent management of these areas while enhancing connectivity and augmenting climate adaptation strategies.

Preventing extinction is an unfulfilled conservation mandate

These insights raise a strategic question: Why have sites harboring rarity and impending global extinction been overlooked? Numerous studies have shown that stabilizing the Earth's climate and reversing biodiversity loss are interdependent goals (4, 27, 28). Efforts and investments to address the climate crisis have overshadowed the attention governments and intergovernmental processes have paid to the biodiversity crisis. The recent Biodiversity COP held in Montreal, Canada in December 2022 (1) was an important milestone that helped spur more urgent and ambitious efforts to protect biodiversity. The COP also linked nature conservation with climate interventions that maintain the Earth's forest cover and carbon sinks, sometimes referred to as nature-based climate solutions (29). Major investments to prevent forest conversion in carbon-rich regions, such as the Amazon Basin, the Congo Basin, and boreal regions, are essential and must be afforded a high priority as some of the last remaining wilderness areas. However, a focus on unprotected rare species areas is needed as the world sets about to expand the protected area network from 17% today to 30% or more by 2030.

Our results corroborate observations that conservation efforts are failing to target regions rich in rare species (30). Only 7% of the 1.2 million km^2 added to the global protected area estate over the past 5 years covered unprotected species rarity sites. These included protected areas that had been established prior but had only recently been recorded in the WDPA—the actual expansion of protection during this period could be even smaller. Several analyses point to a pattern where the addition of new protected areas to the global coverage is largely attributable to areas characterized by low agricultural productivity (31) and has had limited success in protecting threatened species (32). Clearly, the combined efforts of international and local conservation NGOs, foundations, and government agencies to increase protected area coverage to avoid extinctions and extirpations of species need greater support. This analysis shows that this will not happen *de facto* even with 30x30 goals given the limited progress over the past 5 years.

Of most concern is that only 2.4% of newly created protected areas added to the WDPA were in the tropical and subtropical moist forest biome, which contains by far the highest numbers of Conservation Imperatives. In contrast, 69% of protection occurred in the temperate broadleaf and mixed forests biome, 14% in the boreal forest/taiga biome, and 6% in the temperate conifer forest biome—none of which contain high numbers of Conservation Imperatives. As a result, a targeted effort is now required to secure the remaining fraction of rare unprotected species sites before more land conversion occurs and without leaving to chance the selection of new protected areas. Our results yield a surprisingly low number of Conservation Imperatives in the five ecoregion complexes that make up the endemism-rich Mediterranean scrub biome. This finding may be because this biome is one of the most heavily converted among the 14 terrestrial biomes and much of what remains is either protected or so degraded that the fractional land cover analysis inadvertently removed areas that are still viable.

Preventing extinction is affordable and doable

Using the Conservation Imperatives identified in this analysis, a starting strategy that targets the 10 ecoregions within each of the four tropical realms containing the highest number of sites could put 63% of all identified sites under conservation stewardship and represent 12 different biomes. With the geographic concentration of Conservation Imperative sites, this approach will retain representation across distinct biomes and realms (7, 33). The land value for those sites is estimated at US$59 billion (90% probability of US$29–US$108 billion). Focusing more narrowly on the 10 Neotropic ecoregions containing the largest number of Conservation Imperatives would reach 23% of all identified sites, involving a land acquisition cost of US$1.4 billion/year for 5 years in this realm. Several studies have suggested that up to US$224 billion per year for 10 years would be needed to protect nature globally (34). The Conservation Imperatives could help focus these investments in the next 5 years to protect sites where irreplaceable biodiversity is concentrated while allowing individual nation-states to formulate longer-term strategies to address fewer threatened taxa, habitats, and ecological processes.

Factors affecting the cost of Conservation Imperatives

While land purchase or leasing values provide a starting point for costs, a diversity of approaches will be needed to secure the

FIGURE 5
Expansion of protection in species rarity sites in World Database on Protected Areas (WDPA) between 2018 and 2023 after overlaying the fractional land cover. Green polygons show unprotected species rarity sites that have gained protection between 2018 and 2023, representing only 7% of the global increase in protection coverage. Magenta polygons represent sites that remain unprotected in 2023.

protection of Conservation Imperatives. Whereas traditional land trust models focus on the purchase of land for private management, options such as community reserves, government re-designations, private sector commitments, and other effective area-based conservation measures (OECMs) may be more effective, less costly, and more sustainable. Where national governments incorporate the creation of new protected areas into their sovereign biodiversity strategies as a unique contribution, the global cost of the initial protection of Conservation Imperatives will drop dramatically.

Conservation Imperatives that are adjacent to or within 2.5 km of an existing reserve could be much cheaper to manage than isolated Conservation Imperatives. This would especially be true where entities or agencies responsible for protecting nearby reserves could extend management protocols to the adjacent Conservation Imperatives. Alternatively, where these adjacent lands constitute buffer areas or corridors, they could be managed as community reserves. Promoting this landscape approach to reserve management will help ensure these protected areas remain home to the rare and endangered species they protect, even in a rapidly changing world.

As the best conservation strategy will depend on site conditions and land tenure, much of the work to secure Conservation Imperatives will depend on close collaboration with local groups, communities, and governments. For example, 17% of Conservation Imperatives are located within current and historical Indigenous lands (4). Indigenous Peoples and Local Communities (IPLCs) have been among the most effective stewards of biodiversity, and recognition of land rights can play an outsized role in protecting people and biodiversity (4, 35–37). Resource management by local communities can further secure the protection of millions of hectares of critical habitat within sustainable-use forest reserves, such as Amazonian floodplains (38), with the added bonus of raising thousands of local households above the poverty line (39). Where this strategy is appropriate, funding through conservation payments could provide a viable means to pay for site protection and restoration (40, 41).

Finer scale assessment of Conservation Imperatives

Conservation Imperatives can serve as a starting point to guide biodiversity protection commitments from the public and private sectors. Efforts are now underway to finance Conservation Imperatives in 5 of the top 10 countries (Table 6) for sites deemed appropriate for land purchase through private philanthropy. By the end of 2024, similar initiatives could be underway in all of the top 30 countries. Many companies are now developing strategies to become “nature positive” by avoiding impacts on biodiversity-sensitive sites and increasing financial commitments to nature and biodiversity. Conservation Imperatives should be considered for such plans, and can guide the direction of globally flexible resources toward the highest priority targets. These discrete sites are measurable and relatively

TABLE 7 Predicted cost per km^2 and total purchase cost for securing Conservation Imperatives (2023) within tropical latitudes by realm.

Realm	Mean cost/km^2 (US$)	Mean acquisition size (km^2)	Mean total cost (billions US$)	90% probability (billions US$)
Afrotropic	32,548	21,811	38.53	24.39–59.70
Australasia	5,800	131,750	1.59	1.19–2.11
Indomalayan	361,840	1,840	90.39	72.36–112.49
Nearctic	29,545	14,911	0.14	0.08–0.22
Neotropic	75,010	11,025	28.39	23.84–34.02
Palearctic	61,082	7,441	9.50	3.58–19.70

All costs are in 2023 US$. The mean total cost and 90% probability intervals are reported in billions of dollars.

straightforward to monitor and thus could appeal to companies concerned about clearly defined nature-positive outcomes. Of course, in all cases, the local context must be assessed to ensure that conservation actions will be sustainable and support local and Indigenous communities where applicable.

Conservation Imperatives can also act as "anchor points" or connectivity nodes in comprehensive conservation planning efforts. Multicriteria analysis and decision-making platforms can utilize Conservation Imperatives to optimize broader strategies for designing compact and connected protected area networks at the national, ecoregional, or subnational levels (42). Systematic conservation planning can also prove valuable, although these assessments must take into account natural, financial, social, human, and institutional factors that are best assessed and finer spatial scales (8). Existing planning tools such as Marxan (9) and new tools allowing dynamic conservation planning from automated satellite-based habitat monitoring (43) could underpin these regional assessments.

One of the most critical aspects of these fine-scale assessments is determining the viability of sites. A number of Conservation Imperatives that are not adjacent to existing protected areas are small fragments. The long-term viability of these sites and the endangered populations they contain must be subjected to feasibility analyses, such as those conducted recently for a subset of mammal species (10). These in-depth analyses can also better assess the dynamic nature of threats, model the effects of climate change, and incorporate other features.

Efforts to reach the 30×30 goal will incur long-term costs for protection and restoration. As assessments of Conservation Imperatives move to the country, ecoregional, or landscape scales, the work of local teams of scientists and planners to identify critical areas for restoration and tap into these resources could help safeguard many threatened Conservation Imperatives. Such funding is typically earmarked for restoring lands by allowing for natural regeneration or targeted re-planting (preferably with native species) and is not applicable to land purchase. However, time frames for restoration of degraded habitats can be on the order of 5–20 years or more. A central point of our paper is that the Conservation Imperatives require protection within the next 5 years. This urgency is underlined by two levels of extinction crisis documented by conservation biologists: the accelerated rates of species extinction compared to the historical background rate (32, 44) and the extinction of small populations (45). So, these conservation targets—safeguarding the last populations of rare and endangered species and the protection and restoration of habitats—exist on different timelines.

Gaps in our approach

The largest gap in our approach occurs where adding new parcels alone will not achieve the desired outcome of avoiding extinctions. The best examples of this problem are where exotic invasive species are introduced into tropical archipelagos and where poaching of endangered species, particularly keystone species, remains unchecked. In the first instance, simply setting aside land will not guarantee a future for island endemics that have evolved in the absence of exotic invasive herbivores, omnivores, and carnivores, invasive plants, or new diseases. Even those archipelagos that contain formally protected areas are subjected to these threats. Here, targeted eradication and control campaigns are the primary approaches to prevent extinctions, and funding is desperately needed to conserve the large number of tropical flora and fauna on remote islands facing these threats. In the second instance, excessive hunting and poaching of large mammal species could remove critical species whose presence or abundance is essential to maintain critical ecological function. New technologies are emerging to assist those charged with protecting endangered populations and should be part of this global funding effort to avoid extinctions (46).

Conclusion

Conservation Imperatives can contribute to a science-based priority-setting strategy for expanding the global protected area network to at least 30% by 2030, which is in line with ambitious targets outlined in the Kunming-Montreal Global Biodiversity Framework. Area-based conservation targets have moved to the forefront of conservation, and we welcome this approach.

Embedded in the area-based approach, however, should be the commitment to protecting irreplaceable sites harboring rare and endangered biodiversity as we strive towards 30×30. Conservation Imperatives occupy only a small portion of the emerging global conservation portfolio but offer high-quality opportunities to protect the diversity of life on Earth.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsci.2024.1349350/full#supplementary-material. See Appendix for additional details.

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Statements

Author contributions

ED: Writing – original draft, Writing – review & editing, Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation. AJ: Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal Analysis. NH: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization. AL: Writing – original draft, Writing – review & editing, Conceptualization, Formal Analysis, Investigation, Project administration, Validation, Visualization. CVy: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Supervision, Validation. KB: Writing – original draft, Writing – review & editing, Conceptualization, Funding acquisition, Supervision, Validation. GA: Writing – original draft, Writing – review & editing, Methodology, Software. CB: Writing – original draft, Writing – review & editing, Resources. GC: Writing – original draft, Writing – review & editing. RC: Writing – original draft, Writing – review & editing, Resources. RD: Writing – original draft, Writing – review & editing. OF: Writing – original draft, Writing – review & editing. SH: Writing – original draft, Writing – review & editing, Funding acquisition. BL: Writing – original draft, Writing – review & editing. HM: Writing – original draft, Writing – review & editing. FP: Writing – original draft, Writing – review & editing, Visualization. DO: Writing – original draft, Writing – review & editing. BP: Writing – original draft, Writing – review & editing. CP: Writing – original draft, Writing – review & editing. RP: Writing – original draft, Writing – review & editing. AR: Writing – original draft, Writing – review & editing. CVe: Writing – original draft, Writing – review & editing, Resources. EW: Writing – original draft, Writing – review & editing. AZ: Writing – original draft, Writing – review & editing.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material. Shape files of Conservation Imperative sites are not publicly available due to restrictions of the original data layers from which they are derived. Land price data is not publicly available due to privacy restrictions from the data owners and the sites that were funded.

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Conflict of interest

Authors AR and AZ are employed by the company Planet Labs PBC. The company was not involved in the study design, collection, analysis, interpretation of data, the writing of this article, or the decision to submit it for publication.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor HP declared a past collaboration with the author KB. The reviewer JK declared a shared research project Global Renewables Watch with the author AZ to the handling editor, and declared a collaboration with the author KB which started after peer review of the present manuscript.

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Appendix

See Supplementary Material (Presentation 1) for information on the creation of the species rarity layer (2018), caveats and sources of error of the fractional analysis and cost assessment, and supplementary tables and figures:

- SM Table 1. The six biodiversity datasets comprising the species rarity layer and their 923 terrestrial areas.
- SM Table 2. Distribution of Conservation Imperative sites by ecoregion. (See Supplementary Spreadsheet.)
- SM Table 3. Distribution of Conservation Imperative sites by administration. (See Supplementary Spreadsheet.)
- SM Table 4. Model selection table with AIC and R2 values.
- SM Table 5. Model estimates for the top candidate model using realm purchase size, purchase type per capita GDP, and population size.
- SM Figure 1. Locations of project cost data.
- SM Figure 2. Probability distributions for the predicted mean cost per hectare and total land costs.
- SM Figure 3. Maps of Conservation Imperatives in A) the Philippines, B) Brazil, C) Indonesia, D) Madagascar, and E) Colombia.
- SM File. R Code for land cost model fitting and simulation.