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Article

Conservation Imperatives: Securing the Last Unprotected Terrestrial Sites Harboring Irreplaceable Biodiversity

Eric Dinerstein ^{1,*}, Anup R. Joshi ², Nathan R. Hahn ¹, Andy T.L. Lee ¹, Carly Vynne ¹, Karl Burkart ³, Greg P. Asner ⁴, Charlotte Beckham ⁵, Gerardo Ceballos ⁶, Richard Cuthbert ⁵, Rodolfo Dirzo ⁷, Oliver Fankem ⁸, Sarah Hertel ³, Binbin Lee ⁹, Haley Mellin ¹⁰, Félix Pharand-Deschênes ¹¹, David Olson ¹², Bivash Pandav ¹³, Carlos Peres ^{14,15}, Rudi Putra ¹⁶, Amy Rosenthal ^{17,18}, Caspar Verwer ¹⁹, Eric Wikramanayake ²⁰ and Andrew Zolli ¹⁷

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Abstract: Ambitious biodiversity goals to protect 30% or more of the Earth's surface by 2030 to prevent the most likely and imminent extinctions require strategic near-term targets. We propose Conservation Imperatives, spanning 164 Mha across 16,825 unprotected sites harboring rare and threatened species. These sites should be prioritized for conservation action over the next three to five years as part of a broader strategy to expand the global protected area network. The expansion of global protected areas between 2018–2023 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 sites are concentrated, at a cost of US\$34 to \$56 billion per year over the next 3–5 years, could prevent the majority of predicted near-term extinctions once adequately resourced. Multiple approaches could achieve this goal: providing rights and title to Indigenous Peoples and Local Communities (IPLCs) conserving traditional lands, government designation of new protected areas on federal and state lands; or land purchase and long-term leasing of privately held lands.

Keywords: Conservation Imperatives; 30 by 30; protected area targets; rare species; land cover fraction mapping; geospatial analysis; land costs analysis

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 (Convention on Biological Diversity, 2022). While conservation biologists, Indigenous Peoples, science-based NGOs, corporate leaders, and other members of civil society have endorsed this target, many have advocated for accelerated action towards protecting half of the terrestrial realm to provide the best chance for humanity to reverse biodiversity loss, stabilize Earth's climate, prevent ecosystem collapse, and avoid future pandemics (Locke, 2015; Pimm et al., 2018; Dinerstein et al., 2020; IUCN World Conservation Congress, 2021).

Either timeline must account for the urgency of preventing numerous species extinctions and extirpations of small populations that could occur before 2030 and beyond. The purpose of this paper is to: 1) make spatially explicit where to act first on a 3–5 year time horizon to reduce the probability of mass extinctions and extirpations; 2) estimate costs to put these unprotected lands under conservation stewardship; and 3) position these investments as the bulls-eye target in a global strategy to prioritize “the first one-percent” on the path to achieving at least 30% of lands and oceans conserved by 2030 (30×30). We refer to these areas as Conservation Imperatives sites, which if protected before 2028, offer an effective pathway to avoiding the sixth major extinction event in the history of life on Earth.

To prevent global extinctions, scientists have mapped endangered biodiversity and evaluated threats to many endemic taxa to predict where species loss is likely to be most swift and severe (Dinerstein et al., 2019, 2020). It has been estimated that unprotected lands harboring range-limited and threatened species cover 2.3% of the Earth's terrestrial surface (Dinerstein et al., 2020). However, the expansion of the protected area network has failed to significantly increase coverage of threatened species ranges over the last decade (Maxwell et al., 2020). Irreplaceable biodiversity contained within unprotected lands should be prioritized for protection as ‘Conservation Imperatives’ and must be accounted for under the 30×30 target and other regional conservation initiatives (Spiliopoulou et al., 2023). Published range data for rare and threatened species contain varying amounts of agricultural, pastoral, and urban lands, making them less useful as a spatially explicit tool for target setting and protected area planning at regional scales. Recent advances in satellite imagery and classification (Gorelick et al., 2017) support more accurate land cover maps to identify developed and degraded lands contained within areas of particular importance for biodiversity at a global level.

Establishing accurate spatial delineation of Conservation Imperatives sites sets the stage for estimating the expected costs of protected area designation, while exploring various funding and protection mechanisms for specific sites. Previous assessments of costs for conservation at the global scale have relied on extrapolation of land values based on agricultural and pastoral potential (Naidoo and Iwamura, 2007; Strassburg et al., 2020). Despite recent calls for datasets reflecting the real costs of land for conservation (Coomes et al., 2018; White et al., 2022), 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 redesignations—affect the true total costs to protect 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 (Coomes et al., 2018).

Here we posed three questions to identify an accurate spatial representation and initial cost of the Conservation Imperatives sites while accounting for recent landscape changes affecting rare species globally. First, where are these sites located and how much natural habitat remain within them? To answer this question, we produce a new set of polygons harboring rare and threatened species and apply a fractional land cover analysis to spatially delineate the remaining areas of habitat blocks of unprotected rarity globally (UNEP-WCMC and IUCN, 2023). Second, do protected areas added during the past five years reflect an increased focus on preventing extinctions? By using recent extents from the World Database on Protected Areas (WDPA), we test the theory that newly protected

lands should comprise a disproportionately large share of Conservation Imperatives sites if protected areas effectively targeted rare and threatened species. Third, how much is the cost of land required to secure the Conservation Imperatives over the next three to five years, and how do these costs differ, if at all, across biogeographic realms? We use empirical data on land purchase and lease from multiple conservation organizations and biogeographic and economic indicators to estimate land costs of the Conservation Imperatives sites for the pantropical region and within each of the seven biogeographical realms (Dinerstein et al., 2017). We then provide a starting point for ecoregion-based prioritizations within each realm, identify important caveats to our approach, and discuss mechanisms including restoration of Indigenous land rights, community forestry programs, and biodiversity credits.

Materials & Methods

Species rarity layer

We combined six widely used data layers employed in published global biodiversity assessments to identify sites holding rare and endangered species (Dinerstein et al., 2020). Using the latest dataset of global protected areas (April 2023) (UNEP-WCMC and IUCN, 2023) as our base map, we sequentially intersected polygons identified to hold rare and threatened species. These include: Alliance for Zero Extinction (AZE) sites, range-restricted rarity of forest species, the 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 construction of the species rarity layer, see (Dinerstein et al., 2020)(SM Table 1). The overlap determines the remaining unprotected segment. These results were then refined using the fractional land cover analysis described below. It should be noted that governments and NGOs are periodically updating the extent and distribution of areas designated as particularly important for rare, range-limited, and threatened species, through the KBA Partnership and other efforts. This analysis uses 2018 as the reference year (Dinerstein et al., 2020).

Fractional land cover analysis

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 (i.e. some layers, such as AZE sites, are delineated at high resolution but of limited spatial extent; other layers, such as plant endemism that are much larger in area, are not). To identify and remove these non-habitat areas, we used Copernicus Global Land Cover Layers CGLS-LC100 Collection 3 at 100 m resolution (Buchhorn et al., 2020) (hereafter Copernicus data) and Google Earth Engine to generate a fractional land cover map that includes fractions of all land cover types occurring in a pixel at 100 m resolution. While higher resolution global products exist, fractional covers were used to rapidly establish an approximate extent of potential habitat outside protected areas at a global scale.

We used seven classes to create this map: Forest, Shrub, Grass, Crop, Urban, Bare ground, and Permanent Water (inland water bodies). We defined Forest using percent tree cover in the Copernicus data that varied by biome, and set cutoff levels based on expert knowledge in each biome and distinguishing ecological characteristics. Forest is defined as pixels with 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 is defined as 50-69% bare soil in this biome. For all other cover types, we did not differentiate percent cover among biomes. Shrub cover is defined as pixels with shrub cover fraction $\geq 30\%$; Grass as grass cover fraction $\geq 50\%$; Bare ground as bare cover fraction $\geq 50\%$; Urban as urban cover fraction $\geq 10\%$; Permanent Water (inland) as permanent water cover fraction $\geq 30\%$; and Crop as 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 by different cover types to unprotected polygons. To calculate the area of habitat (AOH)

(Brooks et al., 2019) of remaining habitat in species rarity sites, we created a filter by masking all land in the Crop, Urban, and Bare ground cover types. We recognize that crops and bare ground can represent suitable habitat for a fraction of species that are threatened or have restricted ranges, but evaluating these individual species' requirements is beyond the scope of a global assessment. In instances where the fractional land cover analysis resulted in small isolated fragments of rare species habitat surrounded by developed/cultivated land, fragments smaller than 1 ha were removed, as the potential for these lands to be converted in the near future would be quite high. Finally, we overlaid the resulting species rarity layer with the world's 846 terrestrial ecoregion boundaries to identify Conservation Imperatives sites (Dinerstein et al., 2017)

The role of newly created protected areas in addressing area of habitat (AOH) for rare and threatened species and populations

We predicted that the increased focus on global extinction of species would result in many new sites where such species and populations occur to have their AOH placed under protection. Specifically, we expected new reserves created between 2018-2023 to cover > 50% of the rarity sites. To test this prediction, we intersected the Conservation Imperative site polygons with the most recent map of the WDPA (April 2023) (UNEP-WCMC and IUCN, 2023). This comparison gives us an estimate of whether the increases in the global protected area estate over the last five years has effectively addressed those rare and endemic species exposed to the greatest risks of extinction. We used IUCN protected area categories of 1-7. While there is debate in the conservation literature over inclusion of categories 5-7 for biodiversity conservation, our data can be further reanalyzed to restrict consideration of only categories 1-4. We chose a more inclusive approach for this global analysis.

Cost assessment

To estimate the cost of placing Conservation Imperative sites under conservation 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 (Quick Response Fund for Nature, n.d.), supplemented by unpublished data from other NGOs focused on land purchase that met our criteria for inclusion. These organizations regularly fund land acquisition, designation and protection projects globally, and all with a higher concentration in the tropics. This portfolio includes a range of projects, including expansion of existing parks and community reserves, establishment of private conservation areas, and creation of community forest reserves. Acquisition costs cover the purchase price and legal and notary fees that comprised up to 10% of the total cost. For leased land projects of varying lengths, we calculated an annual value and then extrapolated the cost per hectare under a 10-year lease, equivalent to the median lease length in the dataset. This puts leases on the same scale as purchase values but assumes that a 10-year lease would be enough to secure the site while efforts are made for a more permanent solution. All costs were converted to 2022 US dollars, and we accounted for inflation in our calculations. We then extracted biogeographical information on the ecoregion, biome, and realm of each project (Dinerstein et al., 2017). 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 (SM 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 approximately normal distribution. We hypothesized that land value could be influenced by biogeographical realm, region, the area of land being secured, type of land acquisition, and country-level economic factors (Tulloch et al., 2021). 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. All continuous covariates were scaled and centered for interpretation. While attributes such as accessibility and agricultural value can also drive pricing, these aspects require localized data that is unavailable globally. The mean per capita GDP and population was extracted based on the country

in which the project began that fell between 2010 and 2020 (World Bank, 2022). A random effect for data source was added to account for possible variation between the different groups that supplied project data. We fit candidate models and used Akaike Information Criterion and conditional R^2 values to select the most informative model for land value (Burnham and Anderson, 2004) (MuMin R Package).

To calculate the price to place Conservation Imperatives sites under conservation stewardship, we used Monte Carlo Simulations (Mooney, 1997) to estimate 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 Imperatives 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 to place all Conservation Imperative sites in the tropical belt under conservation stewardship. We then identified the top 10 ecoregions in each realm harboring the most Conservation Imperative sites and assessed the price to conserve unprotected lands in each ecoregion. We converted all results to US dollars per square kilometer to keep units comparable to the fractional analysis. Code used for model fitting and simulation can be found in the supplementary materials.

Results

After converted and heavily degraded lands were removed from the extent of potential habitat areas, we identified 16,825 sites harboring rare and threatened species, covering 164 Mha or 1.22% of the Earth's land surface (Figure 1). This actual AOH represents a reduction of 46% versus earlier estimates based on published compilation of identified areas of importance for rare and threatened species (e.g. KBAs, Red List sites, etc.). Most of these reductions occurred in larger blocks of unprotected habitat rather than in smaller fragments. For example, the median area reduction per polygon for Alliance for Zero Extinction sites was only 27 km², as these sites typically included only AOH. In contrast, the median area reduction per polygon for rare and endemic plant species from application of the fractional land cover analysis was 668 km² as these were delineated at larger spatial scales and thus incorporated more non-habitat areas.

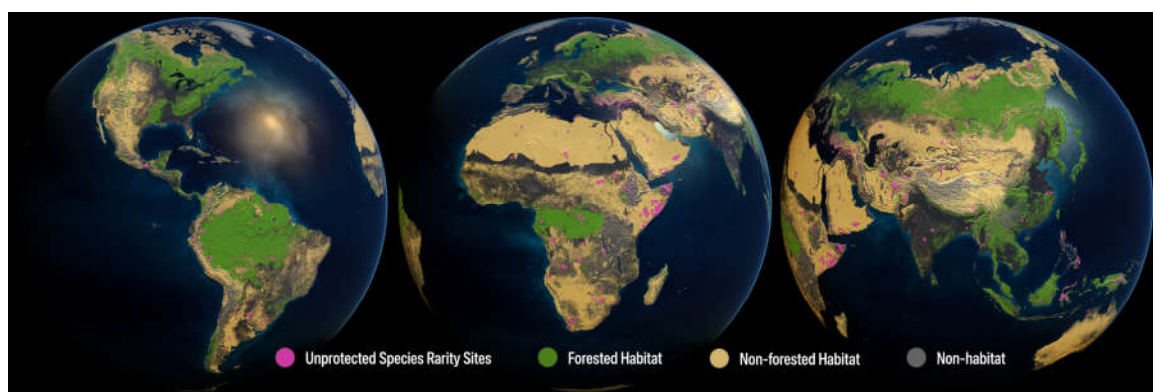


Figure 1. Map of global unprotected species rarity site. Global distribution of the unprotected species rarity sites (magenta area) across predominantly forested habitat (green) and non-forested habitat (yellow), with non-habitat areas (grey) removed from previously designated species rarity sites, covering 1.22%. Non-habitat areas include land classified as urban, agricultural, and degraded.

Reduction in total AOH harboring unprotected rarity also 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 sites, had a 49% reduction in area (Figure 2; Table 2).

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

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%
Palaearctic	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.

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.

Conservation Imperative sites 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 1; Tables 3 and 4; SM Table 2): Eighty-nine percent of the unprotected sites occurred in the four main tropical realms, led by the Neotropics (36%), followed by the Indomalayan (27%), Australasian (15%), and Afrotropical (11%) realms. Among the tropical realms, the Afrotropics contained the most habitat by land area (25% of Conservation Imperatives habitat), while the Indomalayan realm had the least amount of habitat (9%). By biome, the vast majority of Conservation Imperatives sites occurred in the tropical and subtropical moist forests biome (75%) while the remaining 13 biomes ranged from 0–4%. Viewed through the intersection of biomes and realms, the

majority of unprotected sites fall within the tropical and subtropical moist forests biome in the Neotropical realm (38% of all Conservation Imperatives sites), followed by the Indomalayan (34%), Australasian (18%), and Afrotropical (9%) realms. Sorted by ecoregion, the top ten ecoregions with the most Conservation Imperative sites within each of the four major tropical realms hold 57% of all sites globally (Figure 3, Table 5). The top five countries in the world with the highest number of Conservation Imperative sites include the Philippines, Brazil, Indonesia, Madagascar, and Colombia, together accounting for 59% of all sites globally. Over 87% of all Conservation Imperative sites occur in just 30 countries (Table 6).

Between 2018 and 2023, an estimate of 1.2 million km² was added to the global protected area estate (UNEP-WCMC and IUCN, 2023). Of that, the largest extent was located in two ecoregions (#473 Japura-Solimões-Negro Moist Forests and #831 North Arabian Desert, totaling 192,000 km²), but based on our analysis these additions had very little overlap with areas harboring rare and threatened species. In fact, over that same period only 109,779 km², or less than 7% of identified rare and threatened species sites, have been added to the World Database on Protected Areas (Figure 4), leaving the vast majority of these sites at risk of conversion and degradation.

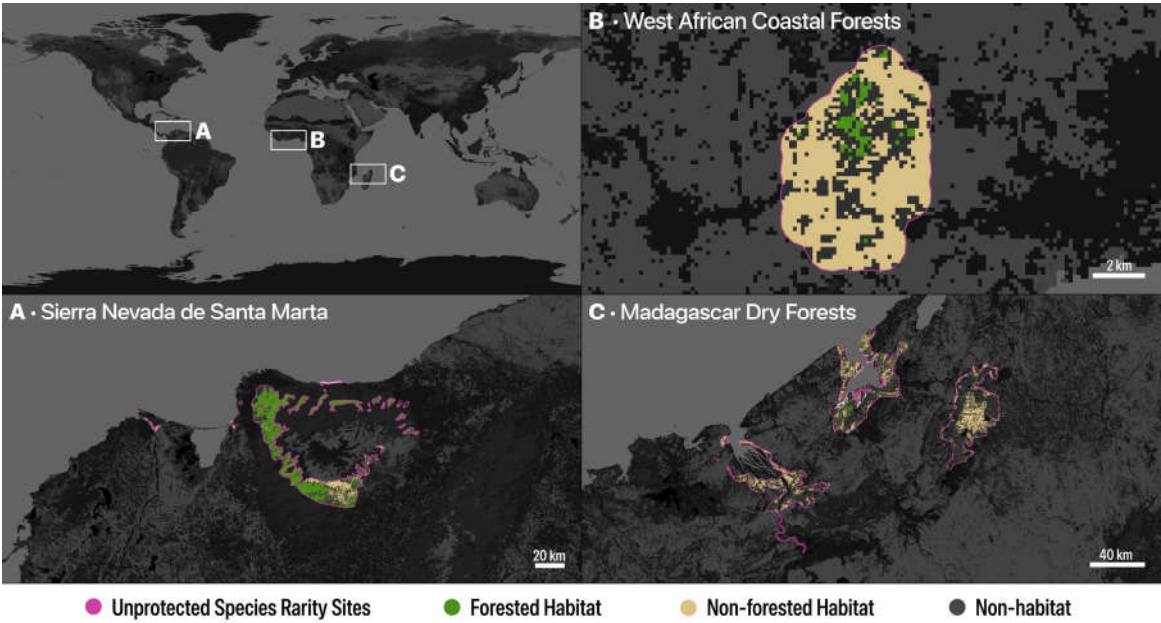


Figure 2. Effect of fractional analysis in identifying and removing non-habitat (Other) areas from species rarity polygons in several regions with high species rarity. Forested and non-forested habitat are retained. A) Sierra Nevada de Santa Marta, Colombia; B) West African coastal forests; and C) Madagascar dry forests.

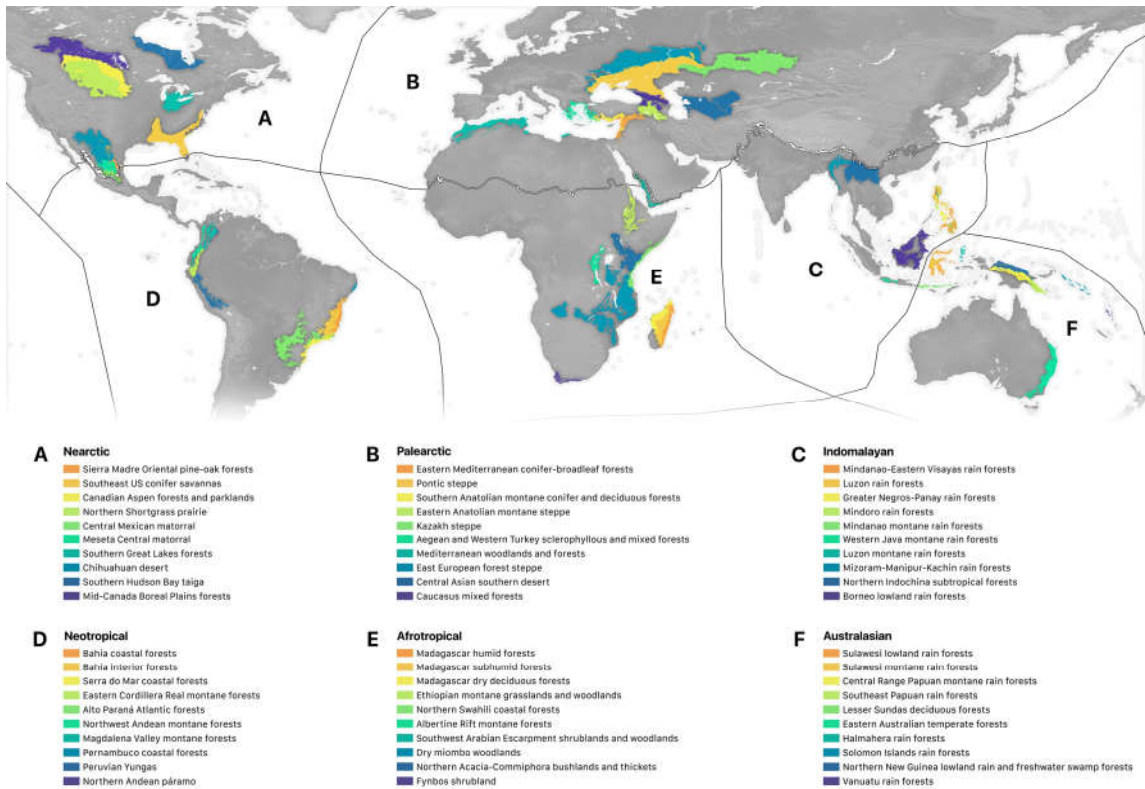


Figure 3. The ten ecoregions in each realm containing the highest number of Conservation Imperatives sites.

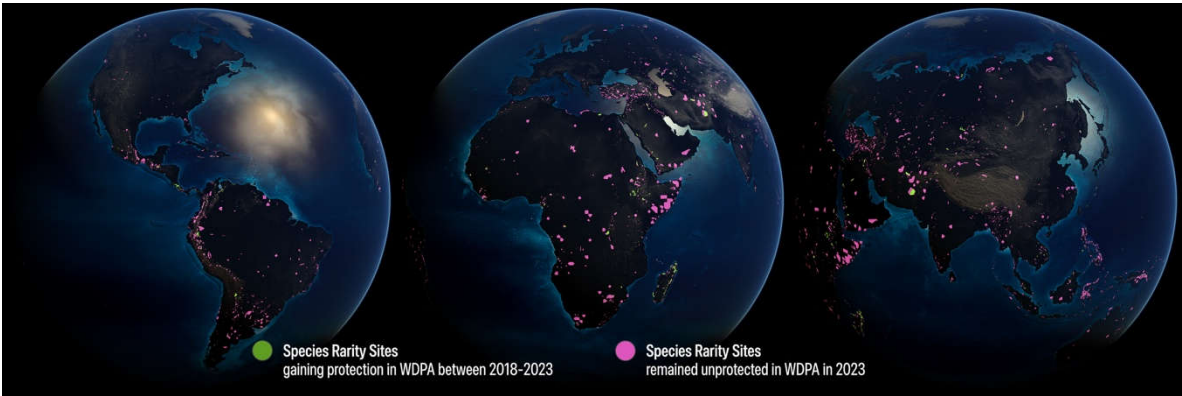


Figure 4. Expansion of protection in Species Rarity Sites under World Database on Protected Areas (WDPA) between 2018 and 2023, after overlaying fractional land cover. Green polygons represent unprotected species rarity sites that have gained protection between 2018 and 2023, representing only 7% of the global increase in protection coverage. Magenta polygons represent sites that remain unprotected in 2023.

Table 3. Distribution of Conservation Imperatives sites (2023) by realm. The four tropical realms account for 89% of all sites globally.

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%
Palaearctic	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%

Table 4. Distribution of Conservation Imperatives sites (2023) in each biome. The Tropical and Subtropical Moist Broadleaf Forests biome alone account for three-quarters of all sites globally.

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%

Table 5. The top 10 ecoregions in each realm with the highest number of Conservation Imperatives sites (2023), and the total remaining natural habitat and estimated cost to place under conservation stewardship. This includes tropical and non-tropical ecoregions.

ID	Ecoregion Name	Total Habitat Area (km ²)	Number of Sites	% of Sites in Realm	Estimated Cost (Million USD)
Afrotropic					
17	Madagascar humid forests	4,295	614	32%	\$337
18	Madagascar subhumid forests	3,836	250	13%	\$302
32	Madagascar dry deciduous forests	3,025	59	3%	\$241
79	Ethiopian montane grasslands and woodlands	725	49	3%	\$56
25	Northern Swahili coastal forests	16,190	48	3%	\$1,201

1	Albertine Rift montane forests	5,200	43	2%	\$352
108	Southwest Arabian Escarpment shrublands and woodlands	2,407	38	2%	\$272
42	Dry miombo woodlands	376	35	2%	\$26
51	Northern Acacia-Commiphora bushlands and thickets	10,976	32	2%	\$710
89	Fynbos shrubland	2,049	29	2%	\$221
Total Cost of Top 10 Ecoregions (% of Total Realm Cost)					\$3.72 Billion (9.2%)
Australasia					
156	Sulawesi lowland rain forests	25,417	1,090	45%	\$197
157	Sulawesi montane rain forests	36,785	421	18%	\$270
139	Central Range Papuan montane rain forests	39,150	379	16%	\$231
153	Southeast Papuan rain forests	15,727	46	2%	\$98
163	Lesser Sundas deciduous forests	1,916	41	2%	\$15
168	Eastern Australian temperate forests	2,192	39	2%	\$31
140	Halmahera rain forests	3,147	32	1%	\$24
152	Solomon Islands rain forests	10,456	25	1%	\$69
148	Northern New Guinea lowland rain and freshwater swamp forests	6,101	22	1%	\$39
159	Vanuatu rain forests	992	18	1%	\$7
Total Cost of Top 10 Ecoregions (% of Total Realm Cost)					\$0.98 Billion (52.4%)
Indomalayan					
247	Mindanao-Eastern Visayas rain forests	22,648	1,561	36%	\$14,948
241	Luzon rain forests	15,139	1,123	26%	\$9,912
231	Greater Negros-Panay rain forests	1,813	190	4%	\$1,184
248	Mindoro rain forests	1,663	178	4%	\$971
246	Mindanao montane rain forests	7,517	139	3%	\$4,880
288	Western Java montane rain forests	709	100	2%	\$467
240	Luzon montane rain forests	2,644	57	1%	\$1,732
249	Mizoram-Manipur-Kachin rain forests	5,395	52	1%	\$3,037
256	Northern Indochina subtropical forests	3,171	44	1%	\$2,097
219	Borneo lowland rain forests	13,993	43	1%	\$8,399
Total Cost of Top 10 Ecoregions (% of Total Realm Cost)					\$47.6 Billion (46.3%)
Nearctic					
327	Sierra Madre Oriental pine-oak forests	1,828	16	9%	\$76
399	Southeast US conifer savannas	1,149	15	8%	\$66
386	Canadian Aspen forests and parklands	121	9	5%	\$7
396	Northern Shortgrass prairie	672	9	5%	\$40
427	Central Mexican matorral	603	8	4%	\$21
432	Meseta Central matorral	819	8	4%	\$31
342	Southern Great Lakes forests	222	7	4%	\$11
428	Chihuahuan desert	3,490	7	4%	\$131
382	Southern Hudson Bay taiga	1,782	6	3%	\$99
376	Mid-Canada Boreal Plains forests	561	5	3%	\$30
Total Cost of Top 10 Ecoregions (% of Total Realm Cost)					\$0.51 Billion (21.5%)
Neotropical					
442	Bahia coastal forests	3,563	1,635	27%	\$410
443	Bahia interior forests	1,161	579	10%	\$138
500	Serra do Mar coastal forests	3,134	434	7%	\$372
460	Eastern Cordillera Real montane forests	18,176	279	5%	\$1,796
439	Alto Paraná Atlantic forests	2,177	192	3%	\$241
486	Northwest Andean montane forests	18,454	192	3%	\$1,888
477	Magdalena Valley montane forests	9,685	156	3%	\$927
491	Pernambuco coastal forests	160	150	2%	\$19
493	Peruvian Yungas	11,658	142	2%	\$1,191
593	Northern Andean páramo	892	121	2%	\$92
Total Cost of Top 10 Ecoregions (% of Total Realm Cost)					\$7.07 Billion (20.3%)

Palaearctic					
791	Eastern Mediterranean conifer-broadleaf forests	6,900	114	7%	\$1,092
735	Pontic steppe	9,506	101	6%	\$1,675
804	Southern Anatolian montane conifer and deciduous forests	12,680	70	4%	\$2,255
727	Eastern Anatolian montane steppe	9,761	57	3%	\$1,501
732	Kazakh steppe	9,220	53	3%	\$1,504
785	Aegean and Western Turkey sclerophyllous and mixed forests	1,577	43	2%	\$270
798	Mediterranean woodlands and forests	2,221	40	2%	\$295
661	East European forest steppe	2,191	39	2%	\$382
819	Central Asian southern desert	3,436	37	2%	\$486
650	Caucasus mixed forests	5,851	36	2%	\$901
Total Cost of Top 10 Ecoregions (% of Total Realm Cost)				\$10.4 Billion (12.9%)	

Table 6. Top 30 countries with the highest number of Conservatives Imperative sites, their percentage total, and median area of sites (km²).

Country	Number of Conservation Imperative Sites	% Total sites	Median area of sites (km²)	Total area of sites (km²)
Philippines	3,355	19.5%	0.46	53,816
Brazil	3,342	19.4%	0.31	35,632
Indonesia	1,893	11.0%	0.50	116,773
Madagascar	968	5.6%	0.37	14,585
Colombia	761	4.4%	0.93	39,827
Ecuador	653	3.8%	0.38	35,026
Papua New Guinea	527	3.1%	0.36	81,800
India	437	2.5%	5.23	20,861
Peru	342	2.0%	13.42	43,590
Turkey	304	1.8%	28.53	50,166
Russia	291	1.7%	54.48	138,436
China	276	1.6%	22.68	41,276
Mexico	230	1.3%	17.22	33,441
Argentina	187	1.1%	40.87	61,285
Australia	137	0.8%	2.31	35,705
United Republic of Tanzania	127	0.7%	0.24	1,041
South Africa	116	0.7%	9.74	40,648
Myanmar	114	0.7%	16.78	22,883
Ethiopia	109	0.6%	0.86	40,513
Kazakhstan	104	0.6%	85.39	58,230
United States of America	102	0.6%	17.78	10,636
Venezuela	93	0.5%	1.77	2,793
Kenya	92	0.5%	0.69	16,297
Vietnam	85	0.5%	5.47	3,274
Bolivia	81	0.5%	16.31	8,612
Yemen	78	0.5%	27.00	6,111
Malaysia	76	0.4%	7.88	9,141
Democratic Republic of the Congo	73	0.4%	13.46	49,350
Syria	70	0.4%	5.16	2,360
Chile	66	0.4%	3.49	2,652
Total of Top 30 Countries	15,089	87.6%		1,076,759

The model of land acquisition costs per hectare included realm, purchase type, purchase size, per capita GDP, and population size performed best and had an R² of 0.76 (SM Table 3). 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 (SM Table 3).

In Monte Carlo Simulations of the cost of placing unprotected habitat under conservation, we found that total land costs of the Conservation Imperatives sites in the tropics are US\$169 billion, with a 90% probability between US\$146 and \$228 billion, assuming variations in the size and type of land acquisitions (purchases and leases) (SM Figure 2). In terms of costs, land transfer was cheapest in Australasia and most expensive in Indomalaya, but somewhat similar in the other realms (Table 7, SM Figure 2b). The Afrotropical, Indomalayan, and Neotropical 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 (SM Figure 2). Land costs for the top ten 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–\$108 billion) and safeguard 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\$204–339 billion).

Table 7. Predicted cost/km² and total purchase cost for securing Conservation Imperatives sites (2023) within tropical latitudes by realm. All costs are in 2022 \$US dollars. The mean total cost and 90% range are reported in billions of dollars.

Realm	Mean cost/km ² (USD)	Mean acquisition size (km ²)	Mean total cost (Billions USD)	90% probability (Billions USD)
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
Palaearctic	\$61,082	7,441	\$9.50	\$3.58–19.70

Discussion

Three key insights emerging from this study elevate the need to prioritize the conservation of rare and threatened species habitat as an urgent near-term target within a larger global biodiversity strategy: 1) Conservation Imperatives sites identified in this study represent a mere 1.2% of the Earth’s terrestrial surface but contain species likely to experience high extinction risk, and thus should be a central component of the 30×30 goals for all countries; 2) Efforts to establish new protected areas have failed to reduce the risks to unprotected rare species; and 3) Financial costs appear to be reasonable, especially in the Neotropics, where ecoregions contain the largest number of species rarity sites.

Why have sites harboring rarity and impending global extinction been overlooked? Numerous studies have shown that the goals of stabilizing Earth’s climate and reversing biodiversity loss are interdependent (Arneth et al., 2020; Dinerstein et al., 2020; Shin et al., 2022). 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 (Convention on Biological Diversity, 2022) was an important milestone, helping 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 (IUCN, 2020). Major investments to prevent forest conversion in carbon-rich regions, such as the Amazon Basin, the Congo Basin, and boreal

regions are certainly essential and must be given a high priority as some of the last remaining wilderness areas. However, many carbon-rich regions have relatively few narrow-range endemics and threatened species.

Targeted investments in preventing extinction in parallel with the conservation of carbon-rich regions are necessary. Given the limited extent of unprotected rare species areas, the two strategies are easily complementary as the world sets about to expand the protected area network from 17% today to 30% by 2030. Given the rapid trend of land conversion near Conservation Imperatives sites, we recommend an initial prioritization of these sites, where possible.

The performance of the global protected area network allocated to concentrations of rarity has come under some scrutiny. Several studies have pointed out that protected terrestrial areas recorded in the World's Database on Protected Areas (WDPA) have performed well, at least on paper, for containing a large fraction of populations representing the Earth's rare species (Pimm et al., 2014). Other analyses point to a pattern where the addition of new protected areas to the global coverage are largely attributable to areas characterized by low agricultural productivity (Venter et al., 2018), and have had limited success at protecting threatened species (Maxwell et al., 2020).

Our results corroborate observations that conservation efforts are failing to target regions rich in rare species. Only 8.8% of the 1.2 million km² added to the global protected area estate over the past five years covered unprotected species rarity sites. Between 2018 and 2023, moreover, only 7% of Conservation Imperatives sites had been added to the protected areas network. These findings are discouraging given the various analyses that point out conservation priorities and the combined efforts of international and local conservation NGOs, foundations, and government agencies to increase protected area coverage and avoid extinctions and extirpations of species represented by small populations.

Only 2.4% of newly created protected areas added to the WDPA were in the tropical and subtropical moist forest biome containing by far the highest numbers of Conservation Imperative areas. In contrast, 69% of protection occurred in the Temperate broadleaf and mixed forests biome, 14% in Boreal forest/taiga, and 6% in temperate conifer forests – none of which contain high numbers of Conservation Imperative areas. As a result, targeted effort is now required to secure the remaining fraction of rare unprotected species, before more land conversion occurs, and without leaving to chance the selection of new protected areas.

The analyses presented here suggest that a targeted global strategy aimed at preventing extinctions is affordable and achievable. This analysis reduces the previous total terrestrial land area containing irreplaceable species to 1.22% globally and 0.74% in the tropics. The modest extent of these areas should make the expected cost of Conservation Imperatives far more achievable over a short time period. If the next three to five years of biodiversity conservation strategy were focused on protecting the Conservation Imperatives, the worst of all possible outcomes for extinction would be averted or blunted. Unfortunately, by narrowing the amount of remaining unprotected habitat for species rarity in the tropical belt to 0.74% of Earth's terrestrial surface, we have greatly diminished opportunities to protect these species. This further demonstrates the urgency of rapid designation of Conservation Imperatives sites.

Using the unprotected sites of rarity identified in this analysis, a starting strategy that targets the ten ecoregions within each of the four tropical realms that contain the highest number of sites could add 57% 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. The land value for those sites is estimated at US\$59 billion. Focusing more narrowly on the ten Neotropical ecoregions containing the largest number of Conservation Imperatives sites would represent 23% of all identified sites, which involve a land acquisition cost of US\$2.4 billion/year for three 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 (Waldron et al., 2020). The Conservation Imperatives could help focus these investments in the next two to five years to protect sites where irreplaceable biodiversity is concentrated while allowing individual

nation states to formulate longer-term strategies to address less threatened taxa, habitats, and ecological processes.

While land purchase or leasing values provide a starting point for costs, a diversity of approaches will be needed to secure protection of Conservation Imperatives. Whereas traditional land trust models focus on purchase of land for private management, options such as community reserves, government re-designations, private sector commitments, and other effective conservation measures (OECMs) may be more effective, less costly, and more sustainable. Of course, where national governments incorporate creation of new protected areas into their sovereign biodiversity strategies as a unique contribution, the global cost of initial protection of the Conservation Imperatives sites would drop dramatically.

The available data on land prices at a global level created some limitations in cost estimates. Namely, localized factors such as road densities, soil fertility, and existing infrastructure can affect prices, but this high-resolution data was not available globally and many of the projects in our database lacked detailed location information. An expanded cost database on land protection projects could help address this information gap, as others have called for (Coomes et al., 2018). Immediate and ongoing protected area implementation and management costs are also a major factor when considering the total expenditure of protecting sites, but these costs depend heavily on site-level factors such as restoration needs, site security and law enforcement, and the type of conservation stewardship. There have been attempts at the regional level to establish ongoing conservation management costs (da Silva et al., 2022), but future efforts need to bring together records of annual expenditures across a range of conservation measures by region in order to create global-scale cost model. For this reason, we chose to focus on land acquisition costs as a first step to expanding the protection of lands harboring rare and threatened species.

Land acquisitions to create protected areas have been successful across a range of countries, which is realized in the dataset collected for this paper. Our dataset spans 938 projects representing 1 million hectares of land acquired to create new protected areas or expand existing ones. Projects can also leverage additional funding to extend impact; For example, the Quick Response Biodiversity Fund unlocked US\$14 of additional funding for every US\$1 raised. These projects also ranged in the type of protection, including private reserves, community conservancies, and community forests. These projects were also relatively small purchases, with a median purchase size of 67.5 hectares. These smaller purchases, generally with a single landowner or small set of landowners, are well-suited for many Conservation Imperatives (median size of 87.6 hectares), where large protected areas and land redesignations may be difficult to achieve without uprooting people and are not necessarily required. It should be noted that geographic coverage of the project database was concentrated in Latin America and Africa. According to the organizations that shared data, this is partly because restrictions on land ownership laws and higher land costs limit project opportunities in other regions of the tropics.

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 sites are located within current and historical Indigenous lands. Indigenous Peoples and local communities have been among the most effective stewards of biodiversity and recognition of land rights can play an outsized role in protecting people and biodiversity (Ban et al., 2018; Dinerstein et al., 2020; Dawson et al., 2021; Duarte et al., 2023). 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 (Campos-Silva and Peres, 2016), with the added bonus of raising thousands of local households above the poverty line (Campos-Silva et al., 2021). Where this strategy is appropriate, funding through conservation payments could provide a viable means to pay for site protection and restoration (Börner et al., 2010; Zander and Garnett, 2011).

Corporate and government stated financial commitments to address biodiversity and ecosystem loss have also become increasingly popular, and large-scale commitments were made at CBD-COP15 to reach 30% protection by 2030 (Naik and Rueedi, 2022; The Nature Conservancy, 2022). Many

companies have recently announced pledges to protect, conserve and restore large land areas. However, these commitments must translate into meaningful commitments for sustainable financing and investment in land protection among corporate sectors. In response to these commitments, the conservation community must be prepared to offer scientifically robust and spatially explicit strategies that protect biodiversity and account for rarity and urgency. As Conservation Imperatives sites represent the most biologically important and threatened places to protect within the 30×30 framework, they can serve as a starting point to guide biodiversity protection commitments from the public and private sector. They can also act as “anchor points” or connectivity nodes in comprehensive conservation planning efforts. Multicriteria analysis and decision-making platforms can utilize Conservation Imperative sites to optimize broader strategies for designing compact and connected protected area networks at the national, ecoregional or subnational levels (Zhang et al., 2021).

Efforts to reach the 30×30 goal will incur long-term costs for protection and restoration. The Conservation Imperatives can support the proper valuation of conservation-related payments through mechanisms such as REDD+ carbon credits, Payments for Ecosystem Services (PES), and Voluntary Biodiversity Credits (VBCs or “biocredits”), allowing such regimes to have a positive impact on rare and threatened species. Biocredits are relatively new, and there are numerous approaches to attributing specific biodiversity values to defined spatial extents. Regardless of the approach, a greater value could be assigned to VBCs that overlap with Conservation Imperatives sites, as these sites, by definition, remain unprotected and harbor rare and threatened biota. Using the Conservation Imperatives map to inform credit issuances could also help to address the problem of additionality. Credits issuances could correspond to habitats that face a threat of conversion leading to the loss of the endemic and rare species that inhabit them. Credits could also incentivize habitat restoration in locations adjacent to Conservation Imperatives sites, thereby reducing the risk of extinction that species may face from habitat loss. High-resolution, high-frequency satellite monitoring could assess the validity of these biodiversity credits, as could low-cost, real-time AI-embedded camera-alert systems incorporated into community-based monitoring protocols.

Conservation Imperatives can contribute towards a science-based approach to prioritizing specific sites as part of the process of expanding the global protected area network to at least 30% by 2030, in line with ambitious targets set forth in the Kunming-Montreal Global Biodiversity Framework. They also respond to the urgency of the extinction crisis we now face. The Earth’s threatened terrestrial biota cannot endure another five years like they have in the previous half-decade. Acquiring and financing Conservation Imperatives sites will keep the focus on what we need to do first to save thousands of species from extinction.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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