ENVIRONMENTAL STUDIES

Gains in biodiversity conservation and ecosystem services from the expansion of the planet's protected areas

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Protected areas safeguard biodiversity, ensure ecosystem functioning, and deliver ecosystem services to communities. However, only ~16% of the world's land area is under some form of protection, prompting international calls to protect at least 30% by 2030. We modeled the outcomes of achieving this 30 × 30 target for terrestrial biodiversity conservation, climate change mitigation, and nutrient regulation. We find that the additional ~2.8 million ha of habitat that would be protected would benefit 1134 ± 175 vertebrate species whose habitats currently lack any form of protection, as well as contribute to either avoided carbon emissions or carbon dioxide sequestration, equivalent to 10.9 ± 3.6 $GtCO_2$ $year^{-1}$ (28.4 ± 9.4% of the global nature-based climate-change mitigation potential). Furthermore, expansion of the protected area network would increase its ability to regulate water quality and mitigate nutrient pollution by 142.5 ± 31.0 MtN $year^{-1}$ (28.5 ± 6.2% of the global nutrient regulation potential).

INTRODUCTION

Protected areas are important for safeguarding the ecological, socioeconomic, and cultural values of our remaining natural ecosystems against both natural and anthropogenic threats (*1*–*3*). Yet, the existing network of protected areas inadequately protects biodiversity, especially threatened species, as well as important ecosystem services such as the storage of carbon and maintenance of fisheries (*4*–*6*). Consequently, there is an urgent need to increase protected area coverage for both biodiversity and human well-being (*2*, *6*). The United States, China, Japan, and Germany, along with more than 50 other countries have recently committed to protecting 30% of Earth's land and oceans by 2030 ("30 × 30") in a lead-up to the 15th meeting of the Conference of Parties of United Nations Convention on Biological Diversity (COP15) (*7*–*9*). While these countries account for more than 35% of the planet's land area, only ~16% of the global land area is currently under some form of area-based conservation, with only 45 countries or territories having met the target of protecting at least 30% of their land area (11 of which have committed to the 30 × 30 target) (*10*).

Achieving this target at the global level will require most countries to rapidly expand their protected area network (*7*, *11*). The expansion of protected areas could be guided by a range of objectives, such as the maximization of biodiversity conservation, ecosystem intactness, or ecosystem service, and has been modeled at national, regional, and global scales (*1*, *12*–*15*). These various strategies often entail trade-offs with other social priorities, including economic development and food production. This necessitates the involvement of multiple stakeholders, including indigenous peoples, local communities, businesses and governments, and the recognition by these stakeholders of the multiple benefits of investing in nature conservation (*10*, *16*). In addition, when choosing which areas to protect, there are likely to be trade-offs between maximizing biodiversity conservation and maximizing other ecosystem services. Such competing socioeconomic and environmental interests and the use of top-down initiatives to create protected areas have spurred much debate (*17*–*19*). Understanding these trade-offs and, consistent with societal objectives, minimizing them will be key to the overall success of 30 × 30.

Here, we model the additional biodiversity conservation, climate-change mitigation, and nutrient-regulation benefits associated with increasing protected area coverage to 30% of the terrestrial area within 238 countries worldwide. Specifically, we account for various objectives associated with protected area expansion by modeling a total of nine scenarios that variously prioritize the intactness of landscapes, conservation of species, and provision of select ecosystem services (fig. S1). Grouping these scenarios by the objectives they fulfill, we compare the potential benefits and trade-offs associated with models that maximize landscape intactness, biodiversity conservation, and ecosystem services, respectively. We also explore the benefits accruing to all three environmental values if nations decide to exceed the 30% target. We consider only natural areas, or areas that retain some natural vegetation cover, and exclude places with relatively lower conservation value such as croplands and urban areas (although many such places have potential for restoration).

RESULTS AND DISCUSSION

To increase protected area coverage to 30% for each of the 193 countries that have not already met this target, an additional 2685 million hectares (Mha) of natural areas must be conserved globally. Of the 1693 vertebrate species whose habitats are currently unprotected, we find that between 765 and 1534 species (45.2 to 90.6%) will inhabit these additional protected areas depending on the modeled scenario (Fig. 1 and Table 1). On average, this corresponds to 208 ± 24 mammals, 215 ± 25 birds, and 712 ± 132 amphibians, and a total of 1134 ± 175 species (95% confidence interval, calculated on the basis of the nine scenarios) that are currently lacking any habitat protection. Roughly half of the species (47% or 535 ± 92 species) that will benefit from this expansion of global protected areas are

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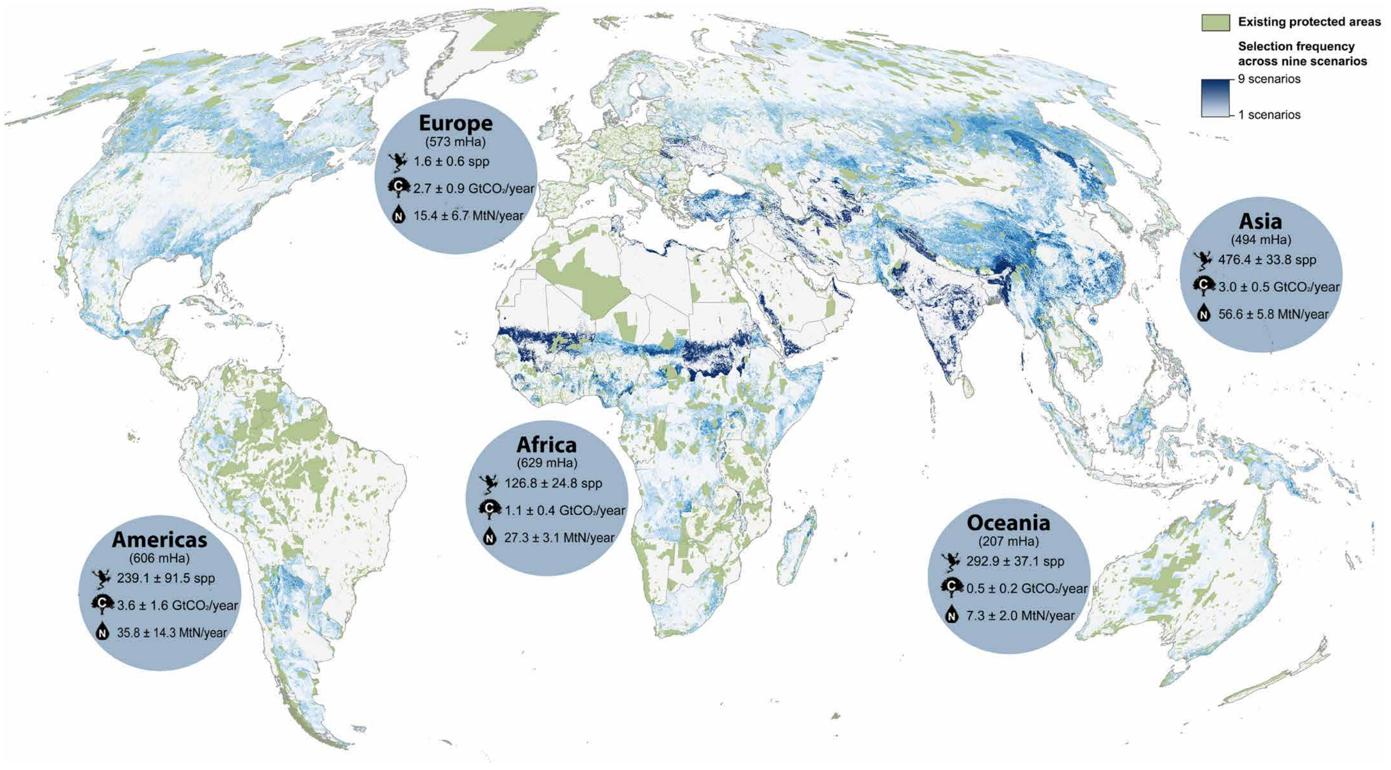

Fig. 1. Magnitude of additional biodiversity conservation, climate-change mitigation, and nutrient-regulation benefits associated with protecting 30% of terrestrial areas in 193 countries globally, across nine scenarios. Insets indicate the total potential benefits within each region's boundaries across a specific area, with values representing average and 95% confidence intervals (calculated on the basis of all nine modeled scenarios).

classified by the International Union for Conservation of Nature (IUCN) as critically endangered, endangered, vulnerable, or near-threatened (*20*). While simply protecting portions of these species ranges might not guarantee their long-term preservation in the face of other threats such as overexploitation and invasive species, especially for migratory species or species with large home ranges, 82% of these imperiled species (439 ± 79 species) are currently classified as imperiled on the basis of their restricted geographic ranges and lack of inclusion in protected areas (*20*–*22*). By ensuring that a minimum of 100 ha of each species' range is protected, the 30% target would represent a key conservation intervention hitherto unavailable to these species (see Materials and Methods) (*22*).

Our assessment of the climate-change mitigation benefits of expanding terrestrial protected areas to at least 30% in every nation under these models is based on scenarios of avoided habitat loss and natural regeneration across forests, grasslands, wetlands, and mangrove areas (see Materials and Methods). Using spatially explicit estimates of the climate-change mitigation potential of these nature-based solutions, we calculated that meeting the 30% target under our nine models would contribute globally to either avoided carbon emissions or carbon dioxide sequestration, equivalent to 10.9 ± 3.6 $GtCO_2$ $year^{-1}$ or 28.4 ± 9.4% of the global nature-based climate-change mitigation potential (Fig. 1 and Table 1). This implies that, globally, up to a fifth of the emission reductions needed to meet countries' unconditional Nationally Determined Contributions could be reached via 30 × 30, along with a third of the reductions associated with limiting global warming to under 1.5°C (*23*).

Last, we modeled the ability of these protected areas to regulate water quality and mitigate nutrient pollution for nearby communities. In particular, we considered the contribution of newly protected natural areas to nutrient (specifically, nitrogen) regulation and the maximum nutrient-regulation potential within these areas (see Materials and Methods) (*24*). These were based on published models, which, while uncalibrated, allowed us to derive the relative amounts of nitrogen regulated in natural areas (*24*). By meeting the 30% target, the expanded network of protected areas is able to regulate an estimated additional 142.5 ± 31.0 MtN $year^{-1}$ of nutrients, which is equivalent to 28.5 ± 6.2% of the global nutrient regulation potential provided by nature areas (Fig. 1 and Table 1) (*24*). This reduces the amount of nitrogen pollution stemming from fertilizer usage, thereby benefiting aquatic biodiversity and enhancing the supply of clean water for local communities that live within the watersheds (*24*).

We also find that these gains are not evenly distributed (Fig. 1) around the globe. Regions such as Asia and the Americas contain more countries with high potential for biodiversity conservation, climate-change mitigation, and nutrient-regulation benefits than do Europe and Oceania (Fig. 2). Similarly, after accounting for the area necessary to achieve the 30% target, countries across Asia and the Americas tend to have greater potential in terms of climate-change mitigation and nutrient regulation. This indicates that certain countries, for example, Indonesia and Malaysia, stand to gain the most from committing to the 30% target (Fig. 2). Considering the high degree of threat to natural ecosystems within these countries, committing to the 30% target could have outsized benefits for their various stakeholders, such as indigenous people, businesses, and governments (*16*, *25*).

Table 1. Global levels of biodiversity conservation, climate-change mitigation, and nutrient-regulation benefits across all nine scenarios, and the proportion of population overlapping with selected areas. Results are reported in absolute values and percentage of global potential. Full breakdown by country is listed in table S1.

Objective	Scenario/ indicator	Biodiversity conservation benefits		Climate change mitigation benefits		Nutrient regulation benefits		Human population overlap	
		Species	%	$GtCO_2$ $year^{-1}$	%	MtN $year^{-1}$	%	Million people	%
Landscape intactness	Human footprint	979	57.8	6.48	16.9	98.5	19.7	32.0	0.4
	Ecosystem intactness	765	45.2	5.67	14.8	95.0	19.0	32.7	0.4
	Biodiversity intactness	913	53.9	4.88	12.7	84.3	16.8	41.3	0.5
Biodiversity conservation	Total species richness	921	54.4	13.79	35.9	175.3	35	89.6	1.2
	Threatened species richness	1067	63.0	11.90	31.0	158.5	31.7	82.6	1.1
	Range-size rarity	1534	90.6	12.49	32.5	166.0	33.2	95.1	1.2
	Key biodiversity areas	1411	83.3	8.42	21.9	125.8	25.1	68.6	0.9
Ecosystem services	Climate-change mitigation potential	1402	82.8	22.82	59.5	145.6	29.1	77.9	1.0
	Nutrient-regulation potential	1216	71.8	11.53	30.0	233.5	46.7	80.3	1.0

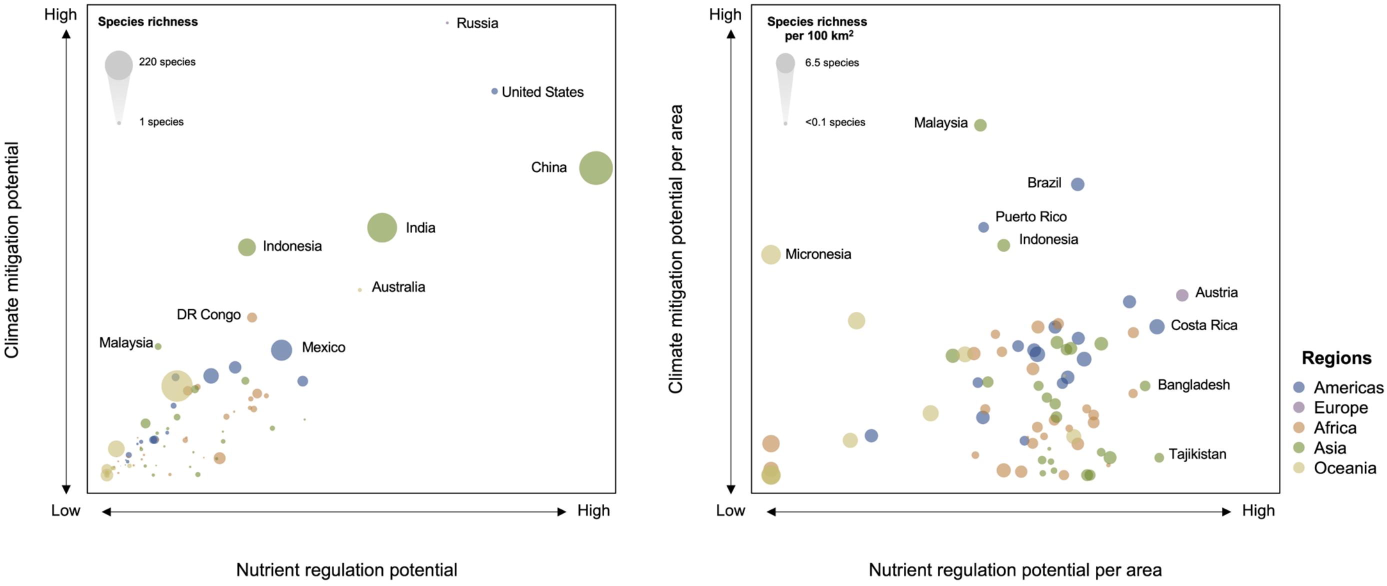

Fig. 2. Relative magnitude of climate-change mitigation and nutrient-regulation benefits across each country, and the relative magnitude of these benefits in relation to the area of expansion needed to achieve the 30% target. Countries (points) are color-coded by region and point size denotes the relative degree of biodiversity conservation benefits.

Our results also highlight an important issue regarding the classification of protected areas. Relying on the standards of the United Nations Environment Programme (UNEP) and areas classified as protected under World Database on Protected Areas (WDPA), we find that in countries such as the United States, China, and India, national-level reporting and inventories can greatly differ from those represented in the WDPA (*26*). For example, in the United States, 14% of existing land area is protected under the UNEP standards, whereas national-level inventory places the total protected area coverage at more than 31% (*12*). Similarly, only 1.7% of China's land area was found to be protected when using WDPA criteria, while other data sources estimate coverage at 15 to 20% (*6*, *27*). This incongruence stems, in part, from national inventories that not only include areas that are protected from conversion to cropland or other anthropogenic land cover types but also permit extractive uses such as logging and mining (*12*, *27*). For such countries, a portion of our estimated gains and benefits may already have been realized depending on the management and use of such areas (*12*, *21*).

Within any country, establishment of additional protected areas is likely to be driven by multiple goals and objectives (*10*, *12*, *27*). In that context, it is helpful to consider in a simple way the degree to which creating protected areas to maximize one goal produces benefits with respect to other goals. If protected areas are designated on the basis of the greatest potential to preserve intact or less disturbed landscapes, we find that 52.3 ± 7.3% of heretofore unprotected species (886 ± 124 species) can be protected. We also find that 14.8 ± 2.3% of global nature-based climate-change mitigation potential can be met with 5.7 ± 0.9 $GtCO_2$ $year^{-1}$ of emissions avoided or sequestered, along with 18.5 ± 1.7% of the global nutrient regulation potential, roughly equivalent to the regulation of 92.5 ± 8.4 MtN $year^{-1}$ of nutrients (Table 1). This is based on three indicators of intact landscape. Namely, we modeled the scenario where areas with the lowest degree of human pressures were preferentially protected (*25*). We also modeled scenarios where such pressures translate to impacts on terrestrial ecosystems (e.g., through habitat loss and fragmentation) (*28*) and impacts on terrestrial biodiversity (e.g., reducing species abundance through changes in landscape and land management) (*29*). By prioritizing the protection of areas with relatively lower levels of human pressure, our model selects areas within each country that are simultaneously the most pristine and have the least competition for existing land use (leading to low opportunity cost); however, these models also confer below-average levels of biodiversity conservation, climate-change mitigation, and nutrient-regulation benefits (*30*).

In comparison, we find that if species conservation is prioritized, greater biodiversity conservation, climate-change mitigation, and nutrient-regulation benefits can be realized. Across all four indicators of biodiversity (total species richness, threatened species richness, relative levels of range-limited species, and size of key biodiversity areas), we find that 72.8 ± 16.6% of all unprotected species can be protected (1233 ± 281 species), along with 30.2 ± 6.0% of global nature-based climate-change mitigation potential (11.6 ± 2.3 $GtCO_2$ $year^{-1}$) and 31.3 ± 4.2% of global nutrient-regulation potential (156.4 ± 21.1 MtN $year^{-1}$; Table 1) (*20*). This supports previous findings on the multiple cobenefits of conservation and reflects the importance of biological diversity for delivering multiple ecosystem services (*1*, *31*).

Last, we considered scenarios where protected areas were selected on the basis of their potential to provide the highest level of ecosystem services. We specifically focused on climate-change mitigation and nutrient-regulation as key ecosystem services that maximize synergies not only between environmental and socioeconomic development but also across targets under negotiation in COP15 (*24*, *32*, *33*). In doing so, we find that potential gains in biodiversity conservation, climate-change mitigation, and nutrient-regulation approach that of scenarios that prioritized the conservation of species. Specifically, 77.3 ± 10.8% of all unprotected species can be protected (1309 ± 182 species), and 44.8 ± 28.9% of global nature-based climate-change mitigation potential (17.2 ± 11.1 $GtCO_2$ $year^{-1}$) and 37.9 ± 17.2% of global nutrient-regulation potential (189.5 ± 86.2 MtN $year^{-1}$) can be met (Table 1). However, we also find that, individually, prioritizing the preservation of land areas for specific ecosystem services can generate substantially higher levels of climate-change mitigation and nutrient-regulation benefits.

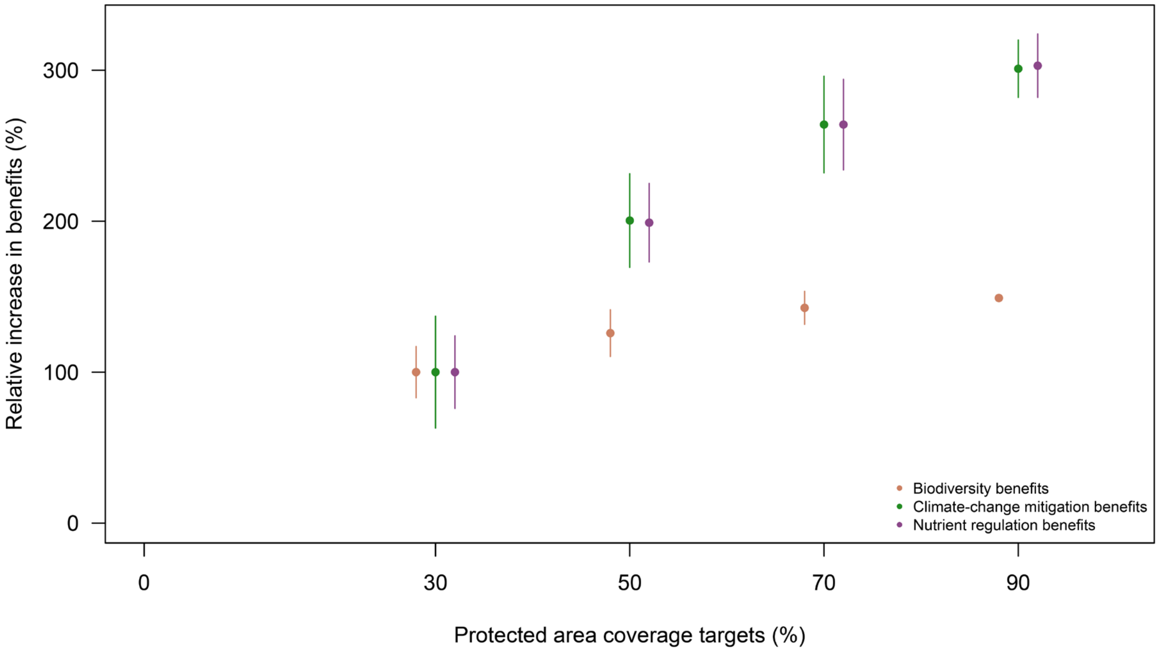

Fig. 3. Effect of increasing protected area coverage on the relative magnitude of biodiversity conservation, climate-change mitigation, and nutrient-regulation benefits. All protected area coverage targets considered are compared to the initial 30% target. Dots indicate the average values across all nine modeled objectives, while uncertainty (lines) represents 95% confidence intervals.

Currently, all nine models assume that safeguarding 30% of terrestrial areas would not result in land-use changes being diverted to other areas (leakage) and that newly created and existing protected areas would remain intact over a long time period. The models also assume that the expansion of protected areas into lands occupied by local communities would generate the same magnitude of benefits to biodiversity and ecosystem services as unoccupied areas. However, both leakage and competition with socioeconomic interests are inter-related issues with ongoing implications for protected area designation and management (*21*, *34*).

Integrating the potential for leakage and socioeconomic impact into our study, we calculated the relative proportion of a country's population that would fall within areas designated to be protected under the nine scenarios (*35*). We find that prioritizing habitat intactness would have the lowest impact on communities that live in and around protected areas. Specifically, 0.45 ± 0.08% (34.9 ± 6.2 million) of the world's population could be affected if habitat intactness was prioritized for protected area expansion, whereas 1.08 ± 0.14% (83.7 ± 10.9 million) and 1.02 ± 0.03% (79.1 ± 2.3 million) of the world's population could be affected if biodiversity conservation and ecosystem service were prioritized, respectively (Table 1). Note that in all scenarios, a very substantial number of people could be directly affected by protected area expansion. Considering impacts on the land rights and socioeconomic activities of people living within these areas, our results draw attention to the potentially substantial impact of top-down conservation initiatives, particularly when such initiatives are derived from external perspectives (*17*, *18*). This has the potential to lead to limited success or uptake of protected area projects within countries and territories with relatively large proportion of populations being affected (table S1) or, even, strong resistance to such initiatives.

In such cases, attainment of 30 × 30 goals will require acceptance (by governments and nongovernmental organizations) of other effective area-based conservation measures beyond protected areas. Habitats owned and managed by indigenous communities, local governments, or private entities and used for purposes such as hunting and other extractive activities, as well as culturally important areas, could be included if they sustain positive conservation outcomes (*12*, *26*, *27*). Another option is to mobilize payments for ecosystem services such as climate-change mitigation and nutrient regulation. For instance, by protecting an area from imminent threat of land-use change, avoided carbon emissions from this area would be available to carbon markets (*32*, *33*). This allows conservation efforts to tap into the growing availability of funds from public and private sectors being directed to climate action (*32*–*34*, *36*). Besides reducing the direct cost of conservation interventions typically borne by governments, nongovernmental organizations, and corporations, such funds can also be directed to local stakeholders through profit sharing and employment, assuming the local stakeholders are amenable. Especially when paired with livelihood improvement schemes, such interventions have been shown to substantially limit leakage while benefiting local communities in countries such as Kenya and Vietnam (*37*). Such schemes that focus on synergistic biodiversity, ecosystem service, and socioeconomic benefits represent a promising means to maximize protected areas while serving and respecting communities in and beyond the affected areas.

As ambitious as 30 × 30 may seem, a growing number of scientists believe that even higher targets are necessary to stem the loss of biodiversity and vital ecosystem services (*5*, *38*). We find that Wilson's "Half Earth" proposal (*38*) that entails protecting 50% of the planet's terrestrial area would result in an outsized increase in climate-change mitigation and nutrient-regulation benefits across all nine scenarios—increasing by 80.5 ± 25.2% and 86.7 ± 25.8% above the 30% target. Biodiversity conservation benefits would increase by an additional 25.8 ± 11.0%, matching findings from previous studies with marginal gains past the 30% target (Fig. 3) (*1*). This, coupled with the relatively high degree of biodiversity benefits attainable under the 30 × 30 target, highlights the importance of this current goal to safeguard species (Table 1). However, expansion of this protected area coverage beyond 30% would be key to derive greater amounts of ecosystem services.

Our study focuses primarily on safeguarding biodiversity and two ecosystem services via expanded protected area coverage. However, more fine-scaled maps of species and ecosystem service distributions would further refine estimates. In addition, other services, such as coastal protection and ecotourism, could also be incorporated into 30 × 30 targets (*33*, *39*, *40*). Our results show that, with careful planning, efforts to expand countries' protected area networks can synergistically achieve multiple targets across global policies such as the Sustainable Development Goals and Article 6 of the Paris Agreement (*23*, *32*, *33*, *40*). However, there are nonetheless important trade-offs among benefits that must be recognized.

We find that achieving the target of protecting 30% of the world's land area by 2030 can greatly benefit both biodiversity and human well-being. Yet, our results also point to the potential for more ambitious targets to nearly double the amount of benefits to people in the form of enhanced ecosystem services. By quantifying the biodiversity conservation, climate-change mitigation, and nutrient-regulation benefits, and using spatial planning approaches, stakeholders within each country can better achieve a multitude of benefits associated with an expanded protected area network.

MATERIALS AND METHODS

Overview of methods

First, we calculated the coverage of existing protected areas, and the coverage needed to close the gap to achieve the target of protecting 30% of all land areas across 238 countries or territories. Second, we assigned the placement of these areas based on nine scenarios representing three key objectives—prioritizing the intactness of landscapes, species conservation potential, and ecosystem services. Third, we quantified the biodiversity conservation, climate-change mitigation, and nutrient-regulation benefits, as well as the proportion of the human population within these areas. Last, we also modeled the potential benefits of surpassing the 30% target.

All calculations were based on data dated between 2012 and 2021 and at a resolution of 1 km. To ensure data standardization, all map layers were resampled to the resolution of optimization (1 km) where necessary, for example, for data sourced from the European Space Agency–Climate Change Initiative–Land Cover (ESA-CCI) (*41*). All calculations were made on the basis of equal-area projections.

Protected area coverage

We classified current protected area coverage on the basis of data from WDPA (*26*). These data incorporate areas officially classified as Protected Areas under all categories and includes other effective area-based conservation measures. This represents the most comprehensive global spatially explicit database of terrestrial protected areas that fall under the standards of UNEP (*26*).

We calculated current protected area coverage as a percentage of each of the 238 countries' land area, as well as the gap needed to achieve the 30% target. Here, we excluded countries that have met or surpassed the 30% target and only modeled the benefits based on the remaining 193 countries. Specifically, we only considered natural areas as protectable and excluded specific land cover types such as bare ground, water, agriculture, and urban areas (*41*).

Prioritizing specific objectives

We then assigned placement of potential protected areas based on the gap needed to reach the 30% target for each of the 193 countries or territories. This was modeled based on nine scenarios, representing three key objectives: intact landscapes, species conservation, and ecosystem services. We used spatially explicit indicators (raster maps) for all nine scenarios and performed calculations on a country level. Cells within each indicator were selected on the basis of their associated objectives (i.e., prioritizing cells with maximum intactness, species conservation, or ecosystem services values), until the 30% protected area target was achieved—ensuring that the highest-ranked areas retain their present conservation value [methods matching Jung *et al.* (*1*)]. In instances where multiple cells were tied for the same indicator value, cell placement was based on random selection (fig. S1).

Intactness of landscapes

We considered three indicators of landscape intactness or integrity, which were calculated on the basis of different aspects (and impacts) of human pressures on the natural landscape. The first indicator was the human footprint index (*25*), which models eight human pressures on the natural landscape. We prioritized the selection of areas with the lowest levels of anthropogenic pressures. The second indicator we considered was the ecosystem intactness index (*28*), which assesses the relative impact of pressures, such as habitat quality and loss, and fragmentation effects on terrestrial ecosystems. Areas with the highest levels of ecosystem intactness were preferentially selected. The third indicator we considered was the terrestrial biodiversity intactness index (*29*), which models the impact of anthropogenic pressures such as climate change, land use, habitat fragmentation, and nitrogen pollution on species abundances of terrestrial biodiversity. Areas with greater biodiversity intactness were prioritized.

Species conservation potential

We used four indicators of species conservation potential or spatially explicit biodiversity levels that were previously quantified by IUCN (*20*). This included species richness across all terrestrial mammal, bird, and amphibian species, as well as the richness of threatened species (species designated as critically endangered, endangered, or vulnerable by IUCN) (*20*). Areas with highest species richness were selected first. We also considered the effect of range size, by using a range-size rarity map. This map reflects the sum total of the proportion of species ranges contained within a given patch of land, across the above three taxa (*20*). Cells with larger range-size rarity values represented areas that contained more stenotopic, endemic, and small-ranging species, and prioritizing the protection of these areas would correspond to preserving greater endemism. We also considered areas that are important for the conservation of species and their habitats that are classified as key biodiversity areas, preferentially selecting larger patches of such areas (*20*).

Ecosystem services

We considered two ecosystem service indicators that also represent separate targets in the upcoming COP15 discussion. These were climate-change mitigation and nutrient-regulation services.

- **Climate-change mitigation:** We modeled this indicator on the basis of the ability of each 1-km cell to provide nature-based climate solutions that avoid carbon emissions or sequester carbon dioxide annually. This was limited to solutions most relevant to area-based conservation: avoided emissions from habitat loss and carbon accumulation through natural vegetation regeneration within a protected area. We modeled these solutions across four main natural habitats, namely, grasslands, terrestrial, peatswamp, and mangrove forests.

Avoided emissions from habitat loss focused on grasslands, terrestrial forests, peatswamps, and mangrove habitats. Grasslands and terrestrial forests were classified according to ESA-CCI (*41*), while peatswamps were classified according to Gumbricht *et al.* (*42*) and mangroves were classified according to Bunting *et al.* (*43*). Forests were limited to areas that were not heavily degraded, with more than 30% forest cover (*44*, *45*) or possessed no small-holder agriculture areas as indicated by the presence of croplands (*41*).

Avoided emissions from habitat loss were calculated on the basis of an estimated annual loss of carbon stocks. Specifically, we estimated the total volume of CO_2 across three pools—aboveground carbon, belowground carbon, and soil organic carbon:

Aboveground carbon: We used a recent global aboveground biomass carbon model by Spawn *et al.* (*46*) to estimate to volume of aboveground carbon for grassland, terrestrial forest, and peatswamp habitats. We also used a global aboveground biomass model by Simard *et al.* (*47*) to estimate the volume of aboveground carbon for mangrove habitats. We applied a stoichiometric factor of 0.475 to convert mangrove biomass estimates to carbon stock values (*33*). We then used a conversion factor of 3.67 to convert carbon stock values to carbon dioxide volume (*32*, *33*).

Belowground carbon: We used the global belowground biomass carbon model by Spawn *et al.* (*46*) to estimate the volume of belowground carbon for grassland, terrestrial forest, and peatswamp habitats. We also estimated the belowground biomass carbon in mangrove habitats by applying an allometric equation from Hutchison *et al.* (*48*) (belowground biomass = $0.073 \times \text{aboveground biomass}^{1.32}$) to the aboveground biomass from Simard *et al.* (*47*). We used the same stoichiometric factor of 0.475 to convert biomass estimates to carbon stock values (*33*) and the same conversion factor of 3.67 to estimate carbon dioxide volume (*32*, *33*).

Soil organic carbon: In addition, to fully consider the carbon stocks of these natural habitats, we used soil organic carbon stock estimates in grassland, terrestrial forest, and peatswamp habitats obtained from the United Nations Food and Agriculture Organization (FAO) (*49*) and mangrove estimates obtained from Sanderman *et al.* (*50*). We applied a conversion factor (3.67) to estimate the volume of carbon dioxide.

To these carbon estimates, we then applied key criteria, such as additionality and decay rates, that enable nature-based solutions to qualify as mitigating climate change. These are in line with rules of the UNFCCC, Kyoto Protocol, and various voluntary certification standards such as Verified Carbon Standard (*32*, *33*).

Additionality: An important component of determining avoided emissions is the concept of additionality, or the volume of carbon dioxide that would have been lost without the intervention of habitat protection from the proposed project. To estimate additionality, we assume that rates of habitat loss would follow a business-as-usual scenario where future loss would match historical patterns (*33*). Habitat loss in peatswamp and terrestrial forests was estimated from Hansen *et al.* (*45*), mangroves from Goldberg *et al.* (*51*), and grasslands from Buchhorn *et al.* (*52*), with duration selected on the basis of data availability. These were calculated as an annualized rate of loss within each 1-km cell. We then applied this estimated annual habitat loss rate to the volume of carbon dioxide calculated above.

Decay rates: We also considered annual decay rates specific to each habitat and its respective carbon pool. We assumed a decay rate of 0.1 and 0.015 across belowground biomass and soil organic carbon pools for terrestrial forests (*32*) and grasslands (*53*), respectively. For mangrove forests, we assumed a decay rate of 0.2 and 0.1 for belowground biomass and soil organic carbon pools (*33*, *54*), respectively. Because of the lack of available data on decay rates for peatswamp forests, we assumed a decay rate of 0.15, taken as the median of all forest habitat values.

We also modeled the natural regeneration of forests in relatively degraded areas across terrestrial forests, peatswamps, and mangroves. This included terrestrial (*41*) and peatswamp forest areas (*42*) with less than 30% forest cover (*45*) and mangrove forests previously assessed as degraded (*44*).

Carbon accumulation in naturally regenerated forests was calculated on the basis of estimates of aboveground biomass carbon accumulation from natural regrowth of terrestrial and peatswamp forests (*55*) and mangrove forests (*56*). We then applied an allometric equation (belowground biomass = $0.489 \times \text{aboveground biomass}^{0.89}$) to estimate belowground biomass carbon (*32*, *57*). In addition, we also considered avoiding business-as-usual flux through the restoration of these habitats (*56*).

Across our calculations of climate-change mitigation potential, we excluded areas such as bare ground and water that cannot function in providing nature-based climate solutions, as well as competing land uses that pose high barriers for entry into protected areas, such as agriculture and urban areas (*41*).

- **Nutrient regulation:** Besides climate-change mitigation potential, we also considered the nutrient-regulation potential of an area. Specifically, we focused on nitrogen regulation as a key indicator owing to data availability and its role as nutrient pollution. We derived a map of nutrient regulation from the product of two spatially explicit estimates of nature's contribution to retaining nutrients (i.e., nitrogen) and maximum potential benefits, both based on current (i.e., 2015) estimates (*24*). As the resultant map is derived from an uncalibrated InVEST model (*24*), we take values as an indicator of relative nutrient-regulation potential. We then preferentially selected areas with the highest potential to retain nutrients.

Calculating impacts

Biodiversity conservation benefits

These were quantified on the basis of the number of species that could gain from conservation intervention via an increase in protected area coverage of their habitats. We focused on the species currently listed and assessed by IUCN and limited our analyses to the 1693 species of mammals, amphibians, and birds that do not currently inhabit any protected areas (i.e., species with ranges that do not overlap with protected area extents). These taxa were selected because they mirrored the input data for a number of the published indicators considered above (e.g., species richness, terrestrial biodiversity intactness); these taxa also have the most rigorously updated and verified species range data from IUCN. We also took steps to reduce inaccuracies—for example, we excluded areas that corresponded to areas where a given species has been introduced but is non-native as well as areas where it no longer occurs (*20*). We then determined the number of species that will have at least 100 ha of their range protected under the 30% targets of each scenario analyzed. This corresponds to the minimum area required for species conservation planning in a majority of studies reviewed by Pe'er *et al.* (*22*).

Climate-change mitigation benefits

These benefits were quantified on the basis of the total volume of carbon emission avoided or sequestered from nature-based climate solutions within the selected areas. These values were based on the same map we produced for the climate-change mitigation ecosystem service (described above). We report climate-change mitigation benefits as a percentage of the global maximum, supplemented with the estimated absolute value.

Nutrient-regulation benefits

These benefits were calculated on the basis of the total nutrient potential benefits provided by selected areas (*24*). This reflects the relative amount of nitrogen retained by vegetation on the landscape that contributes to water quality regulation (*24*). As the values are derived from published uncalibrated models, we primarily report nutrient-regulation benefits as percentage of the global maximum, supplemented with the estimated absolute value.

Proportion of human population

To assess the relative impact of expanding protected areas to achieve the 30% target, we overlaid the selected areas with spatially explicit human population density estimates (*35*). We calculated the relative impact of these selected areas as the percentage of each country's population.

We aggregated and calculated all benefits at a global, regional, and country level, collating results across all nine scenarios. Owing to the lack of uncertainty reporting associated with the source data (e.g., species range and nutrient-regulation maps), we only calculated and reported the average and 95% confidence intervals based on the nine scenarios. In addition, we calculated how frequently each 1-km cell was selected across these nine scenarios. To graphically assess and compare each country's relative gains, we plotted its average transformed (square-root) climate-change mitigation potential and nutrient-regulation potential (Fig. 2). Each country is represented as a point in the graph and is sized according to the biodiversity conservation benefit, which was similarly transformed. We also plotted the relative magnitude of these benefits in relation to the area of expansion needed to achieve the 30% target.

Increasing protected area coverage

We also modeled the potential benefits of adjusting the 30% target. We considered an additional series of scenarios that identified the impacts of increase protected area coverage to 50, 70, and 90%. All nine indicators were similarly considered, and we modeled the biodiversity conservation, climate-change mitigation, and nutrient-regulation benefits across these scenarios.

All analyses were performed in R version 3.6.0 (*58*), using the package "raster" for processing and calculations of raster layers (*59*) and "sf" for shapefiles (*60*). Map visualizations were formed in QGIS (*61*).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abl9885

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