Mapping the planet's critical natural assets for people

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ABSTRACT

Sustaining the organisms, ecosystems, and processes that underpin human well-being is necessary to achieve sustainable development. Here we analyze 14 of nature's contributions to people (NCP) for food, water, and climate security. Using spatial optimization, we identify critical natural assets, the most important ecosystems for providing NCP, comprising 30% (for local benefits) to 44% (for local and global benefits) of total global land area and 24% of national territorial waters. Many of these NCP are left out of international agreements focused on conserving species or mitigating climate change, yet our analysis shows that explicitly prioritizing critical natural assets jointly advances development, climate, and conservation goals. Crafting policy and investment strategies that protect critical natural assets is essential for sustaining human well-being and securing Earth's life support systems.

Human actions are rapidly transforming the planet, driving losses of nature at an unprecedented rate that negatively impacts societies and economies – from accelerating climate change to increasing zoonotic pandemic risk[1,2]. Recognizing the accelerating severity of the environmental crisis, in 2015 the global community committed to Sustainable Development Goals (SDGs) and the Paris Agreement on climate change. In 2022, the UN Convention on Biological Diversity (CBD) will adopt new targets for conserving, restoring and sustainably managing multiple dimensions of biodiversity, including NCP[3]. Collectively, these three policy frameworks will shape the sustainable development agenda for the next decade. All three depend heavily on safeguarding natural assets, the living components of our lands and waters. For instance, restoring and ending conversion and degradation of forests, wetlands and peatlands will sequester 9 Gt CO_2 per year by 2050[4]. Natural assets also underpin most of the SDG targets[1,5]. While ambitious new targets to protect species and ecosystems have been proposed, including "half earth" (conserving half the earth's area for nature)[6] and "30 by 30" (30% protected by 2030)[7], these targets have been criticized for insufficiently accounting for the needs of people, including indigenous and local communities, which are essential for gaining support for broad-scale conservation[8]. Despite the urgency of safeguarding natural assets, we still have limited understanding of the spatial extent of critical benefits that these ecosystems provide to humanity[9].

Leveraging advances in scientific understanding, data availability (Extended Data Tables 1-2) and computational power, we present modeling of 14 NCP globally (Extended Data Fig. 1), the most comprehensive analysis at a fine spatial scale (inputs 300 m, outputs resampled to 2 km for optimization) to date[10,11]. Twelve of these NCP deliver many of their values locally (though some subsequently enter global supply chains), including benefits related to water quality and regulation; provision of food, energy, and raw materials; disaster risk reduction; and recreational benefits (Fig. 1a). We prioritize these 12 "local" NCP at the country level, in contrast to two "global" NCP related to climate regulation (terrestrial ecosystem carbon storage, atmospheric moisture recycling) whose benefits accrue at continental scales or globally. Through multi-objective spatial optimization, we map the planet's *critical natural assets*, the natural and semi-natural ecosystems (Extended Data Table 3) most important to NCP, at local to global scales. We define "critical" natural assets as those providing 90% of current levels of each NCP, because beyond this target there are diminishing returns, with disproportionately more area required to reach incrementally higher levels of NCP (Figure 1b). Our analysis reveals three key findings about critical natural assets: 1) the extent and location of the ecosystems most critical to maintaining current levels of NCP; 2) the number of people benefitting from, and living within, these areas; and 3) the degree of overlap between critical natural assets delivering local benefits and those delivering global benefits.

Critical natural assets that provide 90% of current levels of each of the 12 local NCP assessed (Fig. 1a) occur in only 30% (41 million km^2) of total land area (excluding Antarctica) and 24% (34 million km^2) of marine Exclusive Economic Zones (EEZs), reflecting the steep slope of the aggregate NCP accumulation curve (Fig. 1b). Despite this modest proportion of global land area, the shares of countries' land areas that are critical are highly variable. The 20 largest countries require only 24% of their land area, on average, to maintain 90% of current levels of benefits, while smaller countries (10,000 - 1.5 million km^2) require on average 40% of their land area (SI Table 1). This high variability in the NCP-area relationship

is primarily driven by the proportion of countries' land areas made up by natural assets (which we defined as excluding barren, ice and snow, and developed lands) but even when this is accounted for, there are outliers (Extended Data Fig. 2). Some outliers appear to result from spatial patterns in human population density (for example, countries with dense population centers contrasted with vast expanses with few people, such as Canada and Russia, require far less area to achieve NCP targets) while other outliers could result from ecosystem heterogeneity (greater ecosystem diversity yields higher levels of NCP in a smaller proportion of area, which may explain patterns in Chile and Australia).

Critical natural asset "hotspots" (highest-contributing areas, denoted by the darkest blue or green shades in Fig. 1c) often coincide with diverse, relatively intact habitat near or upstream from large numbers of people. Many hotspots coincide with areas of greatest spatial congruence between multiple NCP (Extended Data Fig. 3). Spatially correlated pairs of "local" NCP (Extended Data Table 4) include those related to water (flood with nitrogen retention, nitrogen with sediment retention); forest products (timber and fuelwood); and those occurring closer to human-modified habitats (pollination with nature access and with nitrogen retention). Coastal risk reduction, forage production for grazing, and riverine fish harvest are the most spatially distinct from other NCP. In the marine realm, there is substantial overlap between fisheries and coastal risk reduction as well as fisheries and reef tourism, but not between coastal protection and reef tourism.

Although these 12 local NCP are not comprehensive[1], they capture, spatially and thematically, many elements explicitly mentioned in the First Draft of the CBD's post-2020 Global Biodiversity Framework (GBF)[12]: nutrition, food security, livelihoods, agriculture, forestry, quality and quantity of water, protection from hazards and extreme events, and access to green and blue spaces. Our results represent a substantial advance beyond recently published maps of biodiversity, ecosystem carbon stocks, fresh water, and marine fisheries[13,14], though they still fall short of capturing relational values of nature. This same multi-NCP optimization approach could accommodate additional NCP as spatial data become available at sufficient resolution and appropriate scales, but sensitivity analyses indicate that results are fairly robust to inclusion of additional NCP. When one of the NCP at a time is dropped from the optimization, the total global land area required only varies by <1-3% (Extended Data Table 5). Furthermore, 62% of the total area on land is shared by all optimization solutions, and 97% of the area is included in 11 of the 12 solutions; similar values are found across most countries (SI Table 1), suggesting that adding more NCP may not substantially change the general spatial patterns or amounts of critical natural assets worldwide.

While every person on Earth depends on nature to meet basic needs, many benefit specifically from the mapped critical natural assets. At least 87% of the global population, nearly 6.4 billion people, benefit directly from at least one of the 12 local NCP provided by critical natural assets, while only 16% live on the lands providing these benefits (and they may also benefit; Fig 2a). While this estimate of "local" beneficiaries likely underestimates the total number of people benefiting (because we consider only NCP for which beneficiaries can be spatially delineated to avoid double-counting), it is striking that the vast majority, 6.1 billion people, live within one hour's travel (by road, rail, boat or foot, taking the fastest path[15]) of critical natural assets, and more than half live downstream (Fig. 2b). In contrast, material NCP may be delivered locally but many also enter global supply chains, making it difficult to delineate beneficiaries spatially. Past studies have calculated that more than 54 million people benefit directly from the timber industry[16],157 million from riverine fisheries[17], 565 million from marine fisheries[18],1.3 billion from livestock grazing[19], and across the tropics alone 2.7 billion are estimated to be dependent on nature for one or more basic needs[20].

Nearly all countries have a large percentage (>80%) of their populations benefitting from critical natural assets, but small countries have much larger proportions of their populations living within the footprint of critical natural assets than do large countries (Fig. 2a; SI Table 2). When people live in these areas, and especially when current levels of use of natural assets are unsustainable, incentives or compensation will be needed to transition to more sustainable use. While protected areas are an important component of

conservation, critical natural assets should not necessarily be protected using designations that restrict human access and use, or they could cease to provide many of their values that make them so critical.

Unlike the 12 local NCP prioritized here at national scales, certain benefits of ecosystems accrue continentally or globally. We therefore optimize two additional NCP at a global scale: vulnerable terrestrial ecosystem carbon storage (i.e., the proportion of total ecosystem carbon lost in a 'typical' disturbance event[21], hereafter 'ecosystem carbon') and vegetation-regulated atmospheric moisture recycling (the supply of atmospheric moisture and precipitation sustained by plant life[22], hereafter 'moisture recycling). Over 80% of critical natural assets for the 12 local NCP are also critical for the two global NCP (Fig. 3). The overlap between the two sets of NCP comprises 24% of land area, with an additional 14% of land area critical for global NCP that is not considered critical for local NCP (Extended Data Fig. 4). Together, critical natural assets for securing both local and global NCP require 44% of total global land area. When each NCP is optimized individually (carbon and moisture NCP at the global scale; the other 12 at the country scale), the overlap between carbon or moisture NCP and the other NCP exceeds 50% for all terrestrial (and freshwater) NCP except coastal risk reduction (whose terrestrial critical areas overlap only 36% with ecosystem carbon, 5% with moisture recycling).

Critical natural assets also show synergies with biological and cultural diversity. Areas prioritized for local NCP at national levels overlap with part or all of the Area of Habitat (AOH[23], mapped based on species range maps, habitat preferences and elevation) for 60% of 28,177 terrestrial vertebrates (SI Table 3). Certain taxa are better represented, like birds (73%) and mammals (66%), but reptiles and amphibians are less well covered (44%), and only 34% of endemics can be supported by critical natural assets for local NCP. Cultural diversity has far higher overlaps with critical natural assets than biological diversity; these areas intersect 96% of global indigenous and non-migrant languages[24] (SI Table 4). Despite the larger land area required for maintaining the global NCP compared to local NCP, global NCP priority areas overlap with only 2% more species (60% of species AOH) and with slightly fewer languages (92%). The degree to which languages are represented in association with critical natural assets is consistent across most countries, even at the high end of language diversity (countries containing >100 indigenous and non-migrant languages). Given this high correspondence, the ways Indigenous cultures benefit from and help maintain critical natural assets is an important research priority emerging from this work.

Data and modeling gaps prevented a broader exploration of issues relevant to terrestrial, freshwater and marine ecosystem management and policy. Although results presented here suggest that nationally prioritized areas for local NCP can deliver on global priorities in many regions, they highlight a need for integrated modeling to represent interactions and feedbacks between different NCP. For example, atmospheric moisture provided by Amazonian forests falls as rain in other parts of South America, supporting ecosystems that provide food, fuel, and other benefits[22]. Further work is needed to move beyond the spatial overlaps explored here toward understanding functional interdependencies between NCP. Our approach could also be used to prioritize restoration of natural assets[25] and identify ecosystems whose NCP may become more important under projected global change (e.g., mitigating disaster risk from climate change or large population shifts through migration that impact demand for NCP). Urban and cropland systems were omitted from this analysis due to the lack of comprehensive, consistent global datasets on land management, but these ecosystems also provide essential NCP. As data and modeling gaps are filled, future assessment of critical natural assets should consider possible gains from sustainably managing and restoring human-dominated systems[26].

In the NCP maps presented here, we represent realized benefits of natural assets—weighted by beneficiary population when feasible—but this understates the range of ways in which natural assets directly and indirectly contribute to people's wellbeing. Limited socio-economic data and lack of reliable models linking NCP to wellbeing indicators preclude more precise valuation of most NCP at the global scale. Additional insight could be gained from mapping critical natural assets that support the most vulnerable or dependent[20] people, including indigenous peoples whose livelihoods and cultural identities directly depend on nature (and indeed overlap substantially with critical natural assets, based on estimates of indigenous language diversity on these lands; SI Table 4), and the poor who lack the ability to procure NCP substitutes. Linking NCP modeling with integrated assessment modeling and general

equilibrium economic modeling could translate the benefits of critical natural assets to macroeconomic outcomes[27], and reveal telecoupling between countries arising from transboundary flows such as via international trade[28]. At the same time, remote sensing and machine learning are elucidating the geography of built infrastructure[29], enabling more compelling assessments of the role of natural assets relative to substitutes. In many cases, critical natural assets produce synergies with anthropogenic assets[3], which should be considered as societies make decisions about protecting NCP and continue to make rapid advances in natural capital accounting[30].

Our analysis enables national and global leaders to identify critical natural assets, priority areas for maintaining a wide range of NCP. Though global analyses can increasingly account for the geography of both natural assets and beneficiaries of NCP, they should be adapted and refined at national or local scales, the scales at which policy implementation occurs, with the best available data and complemented by input from local experts and diverse stakeholders to improve accuracy and public legitimacy[31], and to ensure human rights and diverse human relationships with nature are safeguarded. Prioritizing for NCP would provide a rigorous foundation to enable international financing for climate mitigation, biodiversity conservation and sustainable development to also address the needs of local people, allowing low-income countries to protect the most critical ecosystems for their citizens. We find it encouraging that optimizing the protection of 90% of critical natural assets would require an area comparable to other proposed conservation targets[6,7]. Thus, quantifying and mapping critical natural assets is a vital step forward in empowering actors at all levels to make decisions that benefit both nature and people.

Methods

Modeling Nature's Contributions to People (NCP). The 14 NCP in this analysis (Extended Data Fig. 1) were chosen to span development and climate goals, and to be mappable with spatially explicit data representing the period 2000-2020. The local NCP (Extended Data Table 1) include: **1) nitrogen retention** to regulate water quality for downstream populations (modeled with InVEST[32]; SI Methods Section 1), **2) sediment retention** to regulate water quality for downstream populations (modeled with InVEST; SI Methods Section 2), **3) crop pollination** (modeled with a simplified version of InVEST[33], based on sufficiency of pollinator habitat around pollination-dependent crops.; SI Methods Section 3), **4) fodder production for livestock** (modeled with Co$ting Nature[34]; SI Methods Section 4), **5) timber production** (for commercial and domestic timber, modeled with Co$ting Nature; SI Methods Section 5), **6) fuelwood production** (modeled with Co$ting Nature; SI Methods Section 6), **7) flood regulation** (modeled with WaterWorld[35]; SM Section 7), **8) access to nature** (the number of urban and rural[36] people within a given travel time of any pixel of natural habitat, taking the least-cost path (by foot, road, rail or boat) across a friction layer[15]; SM Section 8), **9) riverine fish catch** (based on spatial disaggregation of reported values[17].; SM Section 9), **10) marine fish catch** (building on the Sea Around Us, improved with Global Fishing Watch data[37]; SM Section 10), **11) coral reef tourism** (modeled in Mapping Ocean Wealth[38]; SM Section 11), and **12) coastal risk reduction** (modeled with InVEST for terrestrial and coastal/off-shore habitats[39–42]; SM Section 12). Global NCP (Extended Data Table 2) include: **1) vulnerable terrestrial ecosystem carbon storage** (the above-ground and below-ground ecosystem carbon lost in a 'typical' disturbance event, rather than the total stock[21]; SM Section 13), **and 2) atmospheric moisture recycling** (modeled with WAM-2[22]; SM Section 14). We use European Space Agency (ESA) 2015, for land cover, Landscan 2017 for population[43] (these were the most current data available at the time we began our analysis); sources for these and additional inputs are listed in Extended Data Table 2.

Attribution of value to natural assets. The first step in identifying critical natural assets is to attribute the magnitude of benefits and, where possible, the number of beneficiaries, to the ecosystems providing those benefits, not merely at the location of the beneficiaries or use of the benefits. We define natural assets as natural and semi-natural terrestrial ecosystems (including working lands like rangelands and production forests, but excluding cropland, urban areas, bare areas, and permanent snow and ice; Extended Data Table 3) and inland and marine waters. Model outputs for pollination and coastal risk

reduction are mapped back to habitat based on the pollinator flight distance and protective distance of coastal habitat, respectively. Population is accumulated on upstream pixels for sediment and nitrogen retention (SI Methods Section 1) and within 1 hour travel time according to a friction surface for nature access (SI Methods Section 8). All other model outputs are coarser than ESA resolution and therefore masked to the relevant LULC types (Extended Data Table 3).

Optimization of NCP. Using integer linear programming (prioritizr, SI Methods Section 22), we identify minimum areas 1) within each country's land borders and marine Exclusive Economic Zones (EEZs) for the local NCP and 2) within all global land area (excluding Antarctica) and all countries' combined EEZ area for the global NCP, to reach target levels (ranging from 5% to 100%) of every NCP. We define the land and marine area for the 90% target as "critical natural assets" because the remaining 10% of aggregate NCP value requires disproportionately more area to reach. Land and marine borders are based on Flanders Marine Institute (2020; Extended Data Table 2), and overlapping claims are excluded from the national analyses. The spatial optimizations of the 12 local NCP for each country are aggregated globally, while the optimization of the two global NCP is conducted at the global scale. In addition to these two main optimizations, we assess the sensitivity of the area and location of critical natural assets (the optimization solution for the 90% target) for different NCP combinations, including each NCP individually and dropping each local NCP from the set of 12 (Extended Data Table 5). We also examine the correspondence between NCP and the robustness of these different solutions, by multiplying the resulting solution rasters of these individual optimizations, in order to calculate the percentage of area shared by different pairs of services (Extended Data Table 4) or the percentage of area shared by all solutions (SI Table 1). We summarize the land and ocean areas required by country in SI Table 1.

Number of people benefiting from critical natural assets. We spatially delineate areas benefiting from critical natural assets to calculate the number of people directly benefiting from those critical natural assets, to compare to the number of people living on the land providing those benefits. For this analysis we are only able to include NCP for which the flow of the benefit can be mapped locally: downstream water quality regulation (sediment retention, nitrogen retention), flood mitigation, nature access, fuelwood provision, and coastal risk reduction. The benefiting areas of material NCP (fish, timber, livestock, crops that are pollinated) that are traded or the location of people who buy those traded goods are not easily mapped, so people benefiting from these NCP are not included in the analysis. However, people within an hour of critical natural assets may provide a surrogate for many of the material NCP that are locally consumed. For water quality regulation, we take the population within the areas downstream (SI Methods Section 1) of critical natural assets. For nature access, we take the population within an hour's travel (by foot, car, boat or rail; SI Methods Section 8) of critical natural assets. Likewise, for the other NCP we take the relevant population downstream, within the protective distance, or a gathering time of critical natural assets. The relevant population for each NCP is considered to be the total global population for nature access and water quality regulation, but is limited to the total population living within 10km of floodplains for flood mitigation, population along coastlines (in exposed areas: <10m above mean sea level) for coastal risk reduction, and rural poor populations for fuelwood. Total "local" beneficiaries are calculated through the intersection of areas benefiting from different NCP, to avoid double-counting people in areas of overlap. We calculate the number of people and percent of relevant population benefiting globally for each NCP (Fig. 2b) and the total "local" beneficiaries globally (Fig. 2a) and by country (SI Table 2).

Overlap analysis. We evaluate how well local and global critical natural assets align spatially with each other, and with biodiversity (terrestrial vertebrate species Area of Habitat (AOH)[23]; SI Methods Section 15) and cultural diversity (proxied by the number of Indigenous and non-migrant languages[24]; SI Methods Section 16), to determine potential synergies between these different potential priorities. To examine the level of overlap between areas identified as critical for the 12 local NCP vs. the 2 global NCP, we calculate the area (globally and by country) where local NCP are selected by the optimization (at the 90% target level) and global NCP are not, where global NCP are selected by the optimization and local NCP are not, and where both are selected by their respective optimizations (the overlap). To calculate the species and languages represented by critical natural assets, we count the number of species whose

AOH area targets overlaps these areas (SI Table 3) and the number of languages partially intersecting these areas (SI Table 4) globally and within each country. See SI Methods Section 23 for more detail.

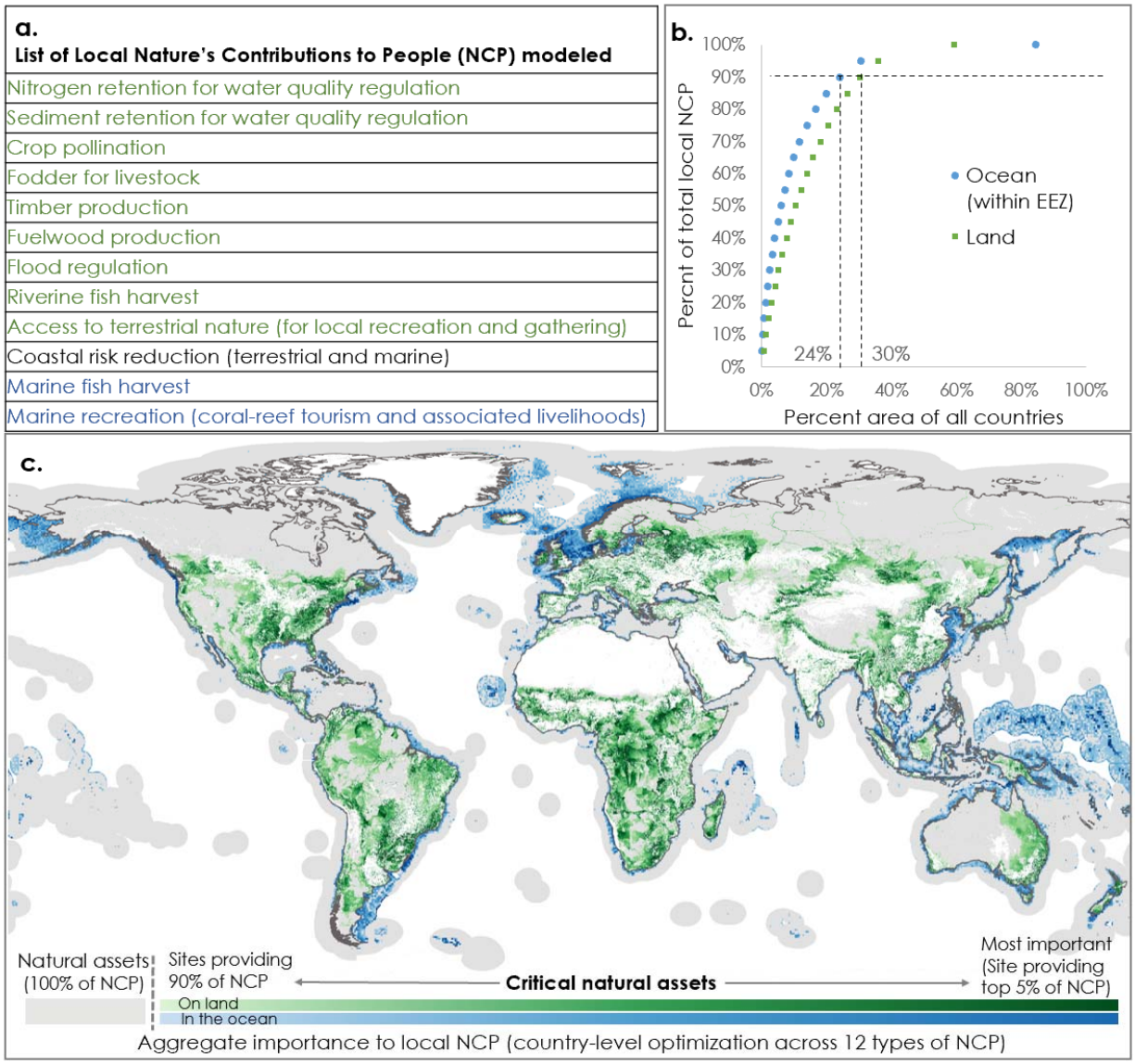

Figure 1. *Critical natural assets, defined as the natural and semi-natural terrestrial and aquatic ecosystems required to maintain 12 of nature's "local" contributions to people (NCP) on land (green) and in the ocean (blue). (a) The 12 local NCP analyzed (i.e., not including global climate NCP, shown in Fig. S4). (b) The NCP accumulation curve, reflecting the total area required to maintain target levels of all NCPs in every country, with dotted lines denoting the area of critical natural assets (90% of NCP in 30% of land area and 24% of EEZ area). Areas selected by optimization within each country are aggregated across all countries to create a single global accumulation curve; see Table S1 for area requirements in individual countries. (c) Map of critical natural assets, with darker shades connoting critical natural assets that are associated with higher levels of aggregated NCP. Grey areas show the extent of remaining natural assets not designated "critical" but included in this analysis; white areas (cropland, urban and bare areas, ice and snow, and ocean areas outside the EEZ) were excluded from the optimization.*

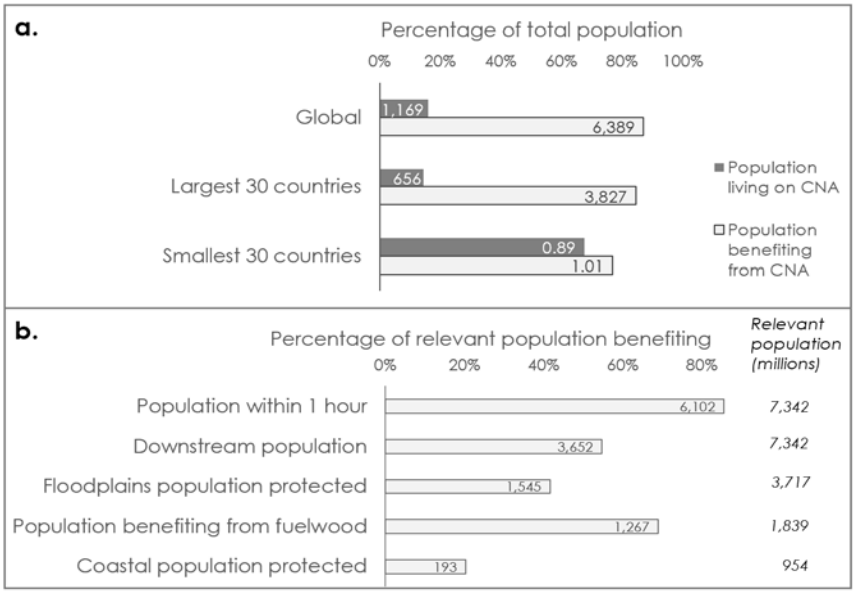

Figure 2. *People benefiting from and living on critical natural assets (CNA). "Local" beneficiaries were calculated through the intersection of areas benefiting from different NCP, to avoid double-counting people in areas of overlap; only those NCP for which beneficiaries could be spatially delineated were included (i.e., not material NCP that enter global supply chains: fisheries, timber, livestock or crop pollination). Bars show percentages of total population globally and for large and small countries (a) or the percent of relevant population globally (b). Numbers inset in bars show millions of people comprising that percentage. Numbers to the right of bars in (b) show total relevant population (in millions of people, equivalent to total global population from Landscan 2017 for population within 1 hour's travel or downstream, but limited to the total population living within 10km of floodplains or along coastlines <10m above mean sea level for floodplain and coastal populations protected, respectively, and to rural poor populations for fuelwood).*

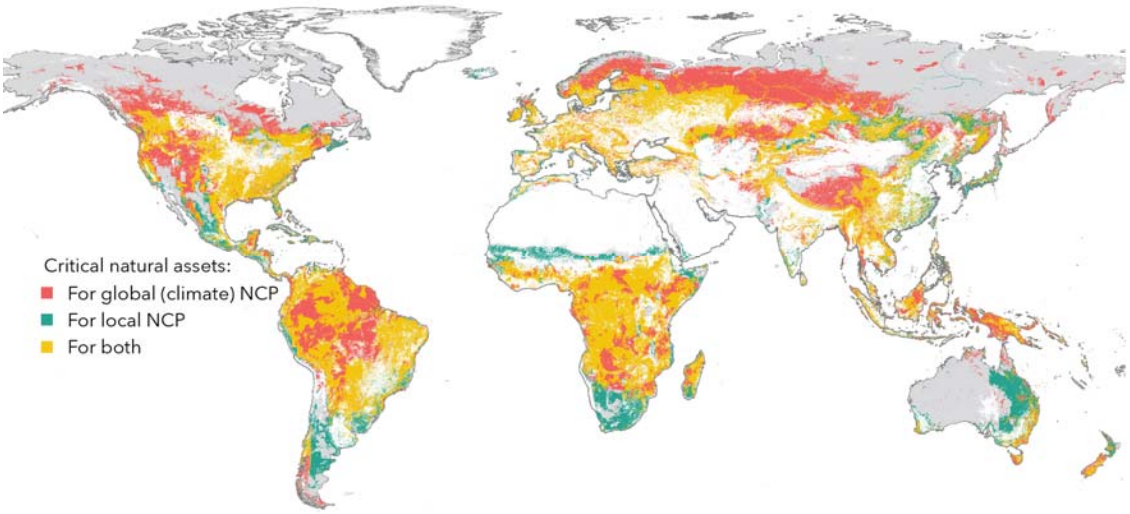

Figure 3. *Spatial overlaps between critical natural assets (CNA) for local and global NCP. Red and teal denote where CNA for global climate NCP (providing 90% of ecosystem carbon and moisture recycling globally) or for local NCP (providing 90% of the 12 NCP listed in Fig 1), respectively, but not both, occur; gold shows areas where the two overlap (24% of the total area). Together, local and global CNA comprise 44% of total global land area (excluding Antarctica). Grey areas show natural assets not defined as "critical" by this analysis, though still likely providing some local values to certain populations. White areas were excluded from the optimization.*

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Additional Information: Supplementary Information is available for this paper. Correspondence and requests for materials should be addressed to bchaplin@stanford.edu.

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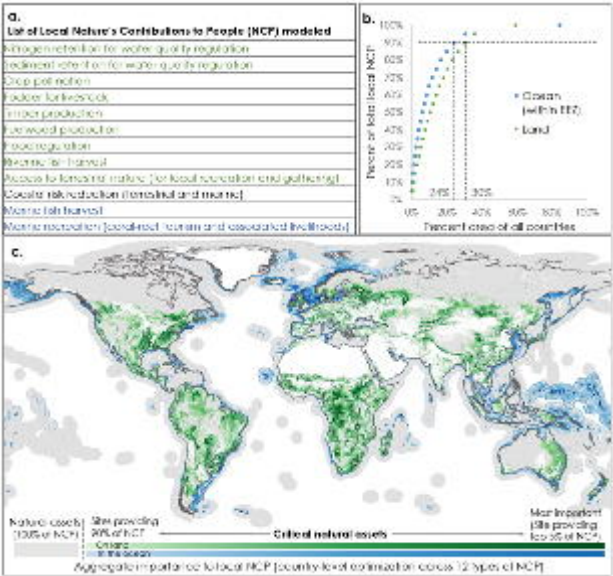
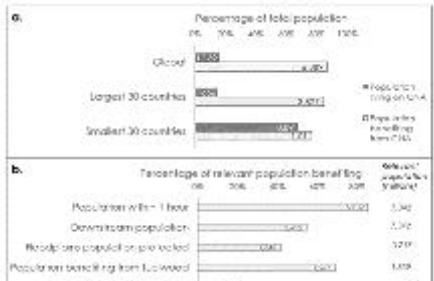
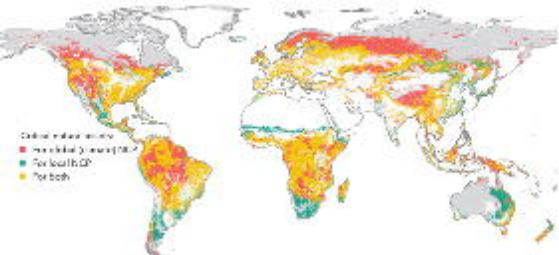

a.
List of Local Nature's Contributions to People (NCP) modeled
Nitrogen retention for water quality regulation
Sediment retention for water quality regulation
Crop pollination
Fodder for livestock
Timber production
Fuelwood production
Food regulation
Riverine fish harvest
Access to terrestrial nature (for local recreation and gathering)
Coastal risk reduction (terrestrial and marine)
Marine fish harvest
Marine recreation (coral-reef tourism and associated livelihoods)
b.
Percent of total local NCP
Percent area of all countries
Ocean (within EEZ)
Land
24%
30%
c.
Natural assets (100% of NCP)
Site providing 90% of NCP
Critical natural assets
Most important (Site providing less 5% of NCP)
On land
In the ocean
Aggregate importance to local NCP (country-level optimization across 12 types of NCP)


a.
Percentage of total population
Global
Largest 30 countries
Smallest 30 countries
b.
Percentage of relevant population benefiting
Population within 1 hour
Downstream population
Population benefiting from fuelwood
Coastal population protected


For both