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THE AMAZON WE WANT

CONNECTIVITY IN THE AMAZON RIVER BASIN: THE CRITICAL ROLE OF INDIGENOUS TERRITORIES AND PROTECTED AREAS

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EXECUTIVE SUMMARY

Preserving ecosystem connectivity across the Amazon River basin (hereafter Amazon basin), including the Andes-lowland Amazon gradient, is critical for maintaining ecosystem functionality, biodiversity, climate resilience, and human well-being.

To identify connectivity patterns in the Amazon basin, we utilized satellite data available in RAISG to map ecosystems connectivity and anthropogenic disruptors. Our analysis revealed widespread predatory human-caused impacts affecting approximately 25% of all ecosystems. Notably, Indigenous Territories and Protected Areas (ITPAs) are found to be key areas for maintaining habitat connectivity across terrestrial, seasonally flooded, and aquatic ecosystems across the Amazon basin.

We conclude that strengthening governance and sustainable initiatives in ITPAs, in partnership with local inhabitants, represents the most expedient, efficient, and cost-effective strategy for conserving ecosystem connectivity in the Amazon basin.

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Key Messages

(i) Ecosystem connectivity in the Amazon River basin is critical for healthy ecosystem functioning, enabling species movement, ecological interactions, and water and nutrient flows that are essential for the long-term stability and resilience of the Andes-Amazon system.

(ii) The Amazon River basin is facing a critical loss of ecosystem connectivity due to rapid deforestation and degradation, occurring faster than any area of comparable size in the world. The crisis is driven by multiple factors, with logging and burning for agriculture and livestock, and regional desiccation under global climate change as the leading drivers.

(iii) Distinct Amazonian ecosystems are under varied pressures that disrupt connectivity: terrestrial lowlands by deforestation, wetlands mostly by fire, and Andean rivers by dams and mining. Dams and illegal mining are the main factors disrupting aquatic connectivity.

(iv) As of 2020, 23% of the lowlands, 24% of the rivers, 25% of the wetlands, and 28% of the Amazonian Andes were negatively impacted by at least one anthropogenic impact. Most of these changes took place in the last 40 years. Areas of greatest loss of connectivity are:

(a) the *Arc of Deforestation* across the southern and southeastern Amazon in Brazil and Bolivia;
(b) the Andean foothills of Colombia, Ecuador, and Peru;
(c) the lowland forests adjacent to the Amazon River in eastern Brazil.

(v) The integrity of Indigenous Territories (~29% of the Amazon River basin) and Protected Areas (~23%) is the most important and viable way to maintain aquatic and terrestrial habitat connectivity in the Amazon basin.

Recommendations

(i) To effectively protect Andes-Amazon connectivity, it is imperative to strengthen and reestablish **effective governance in Indigenous Territories and Protected Areas.**

(ii) Reducing fire risk in the Amazon requires targeted policies that focus on **large-scale deforestation and fire use by agribusiness operations**, including stricter enforcement of environmental laws, penalties for illegal burning, policy reforms, enhanced coordination among stakeholders, community engagement, early warning systems, and increased investment in fire prevention research.

(iii) We recommend establishing **"dam-free" *sanctuary zones* to perpetuate the Andes-Amazon riverine connectivity.** We propose the Japurá, Putumayo-Ica, Beni, Napo, Marañon, Ucayali and Madre de Dios rivers as such *connectivity sanctuaries*, which should also include nearby riverine ecosystems, as a means to maintain water-land dynamics.

(iv) We suggest the following corridors be designated as **biodiversity reserves to maintain terrestrial Andean-Amazonian terrestrial connections:** (a) a northern/Colombian corridor, connecting the Protected Areas Serranía de los Churumbelos, Alto Fragua Indi Wasi, La Paya, Sierra de Chiribiquete, Cahuinarí, Río Puré, Amacayacu, and Indigenous Territories Yaigojé Apoporis, Alto Rio Negro, Balaio, Yanomami, and Médio Rio Negro. (b) A southern corridor, to connect Protected Areas and Indigenous Territories of Peru, including Alto Purus, Manu, Apurímac, and Amarakaeri, and Brazil Indigenous territory of Vale do Javari. (c) In Ecuador, an additional corridor, although hampered by oil concessions, should be established to connect the Cayambe-Coca, Sumaco, and Yasuní National Parks.

(v) **Governance and coordination between Amazonian countries** are essential for protecting and maintaining connectivity in the Amazon at the basin scale. Effective conservation at this scale requires shared monitoring systems and legal and institutional mechanisms that can respond rapidly to threats with bilateral and multilateral agreements. These actions will facilitate cross-border enforcement and prosecution of violators. Regional alert observatories and a robust, harmonized legal framework are keys to ensuring timely enforcement.

(vi) In planning the economic development in the basin, it is essential to uphold the right to **Free, Prior, and Informed Consent (FPIC) for Indigenous Peoples (IPs) and Local Communities (LCs),** particularly in decisions related to extractive industries and large-scale infrastructure in the basin. We advise applying the Precautionary Principle, emphasizing caution, deliberation, and review before enacting large-scale infrastructure projects. We recommend suspending the construction of all new dams that obstruct or divert waterways in the basin, and prioritize the transition to sustainable alternative energies like wind and solar.

(vii) Activities with potentially-high environmental impact, such as mining, oil drilling, and agriculture and livestock farming must undergo a **rigorous licensing process** that includes comprehensive environmental impact assessments. These assessments must follow the Indigenous Peoples and Local Communities' (IPs and LCs) right to free and prior informed consent (FPIC) as required by the ILO Convention 169, the UN Declaration on the Rights of Indigenous Peoples, and by the UN Human Rights Council Res. 39/12. They also should be conducted and monitored by IPs and LCs in partnership with independent institutions, preferably based in the Amazon region (e.g., universities, research institutes, NGOs). Additionally, commodities that originate from the Amazon basin should have transparent supply chains, with information made publically available to consumers and other stakeholders.

(viii) **Abolish in-stream mining operations in all waterways** throughout the Amazon. Ensure all future contracts require funding for enforcement and restoration. Planning for new infrastructure projects must include public or international funds to restore and remediate areas adversely impacted by previous extractive activities.

(ix) Conservation and development (i.e. transport, infrastructure, energy) strategies must **acknowledge and safeguard connectivity** across the many ecosystems within the basin (e.g., wetlands, *terra-firme* forests, naturally open areas, riverscapes), accounting for ecosystem heterogeneity and effective IPs and LCs management .

Background

The Amazon Basin[1,2] is a globally geo-, socio-, culturally and biologically diverse region[3–7], now severely threatened by numerous anthropogenic impacts[8–11]. These impacts act synergistically and, for the first time in human history, we face the functional collapse of Amazonian ecosystem services related to water, nutrient and biodiversity resources[11,12]. This scenario is due to the joint action of local land use changes and global climate change driven by industrial scale economic activities. Alongside with ecosystem destruction and degradation, loss of ecosystem connectivity, which is defined as the degree to which natural processes can occur unimpeded within an area, poses a huge environmental threat, severely disrupting essential ecosystem functions.

We assess ecosystem connectivity in the Tropical Andes and the Lowland Amazon, which constitute a coupled system essential for ecosystem functioning in the tropical America: the lowlands export water vapor that feeds rainfall in the Tropical Andes through aerial rivers, while the Tropical Andes export surface waters to the lowlands[13–15]. Many rivers in the Amazon basin originate in the Andes[16]. The combined flow of the Andean tributaries contributes about half of the Amazon river's annual water flow, and transport massive quantities of sediments, organic matter, and nutrients to the lowlands[14,16]. Furthermore, the Tropical Andes and Amazonian lowland ecosystems share a complex and intertwined evolutionary history that spans tens of millions of years[4,5,16,17] and supports a high diversity of natural and semi-natural (i.e., partially-domesticated) landscapes. As a result, the Tropical Andes-Amazon system is one of the most biodiverse on the planet, with the Amazon being home to at least 10% of global biodiversity[6], with numerous species still unknown to science, and a high level of endemism[6,18–20].

Maintaining ecosystem connectivity between the Tropical Andes and lowland Amazonia is key not only to retain ecosystem functionality, but also to ensure biodiversity conservation and human well-being at local, regional, and global scales. To establish priority areas for Amazonian preservation, it is imperative to incorporate the concept of connectivity. Without the broader concept of connectivity, small reserves are destined to lose their biodiversity and function[9,11], in particular in the face of climate change impacts, such as droughts, as connectivity is essential to facilitate species migrations and ecological adaptation[21,22].

To determine which areas currently maintain ecosystem connectivity at the Amazon basin scale, six major human activities that disrupt connectivity in the region were mapped using satellite data from RAISG[23, 143] (**Figure 1**). Specifically, we used a resistance based methodology (see Material and Methods) to assess connectivity between the Tropical Andes and the Lowland Amazon through riverine, wetlands, and terrestrial ecosystems. The analysis shows that 23% of the Amazonian terrestrial lowlands, 24% of the rivers, 25% of the wetlands, and 28% of the Amazonian Andes are impacted by at least one category of activity (**Figure 1**). The most impacted areas are located south of the Amazon River, in the Brazilian Shield[24], and in eastern Amazon[24] (**Figure 1**). When pooled across ecosystems, mining and deforestation are the most impactful activities altering connectivity across the Amazon (**Figure 1**). Overall, about a quarter of all ecosystems are impacted, disrupting connectivity in a spatially heterogeneous fashion. Although one or more of these activities are found within several ITPAs (**Figure 2**), these maintain significant higher connectivity of terrestrial, wetlands, and riverine ecosystems across the Amazon basin (**Figure 2**). Our results highlight important areas that should be prioritized, amplified, and strengthened to maintain ecosystem connectivity and ensure the resilience of Amazonian socio-ecological systems.

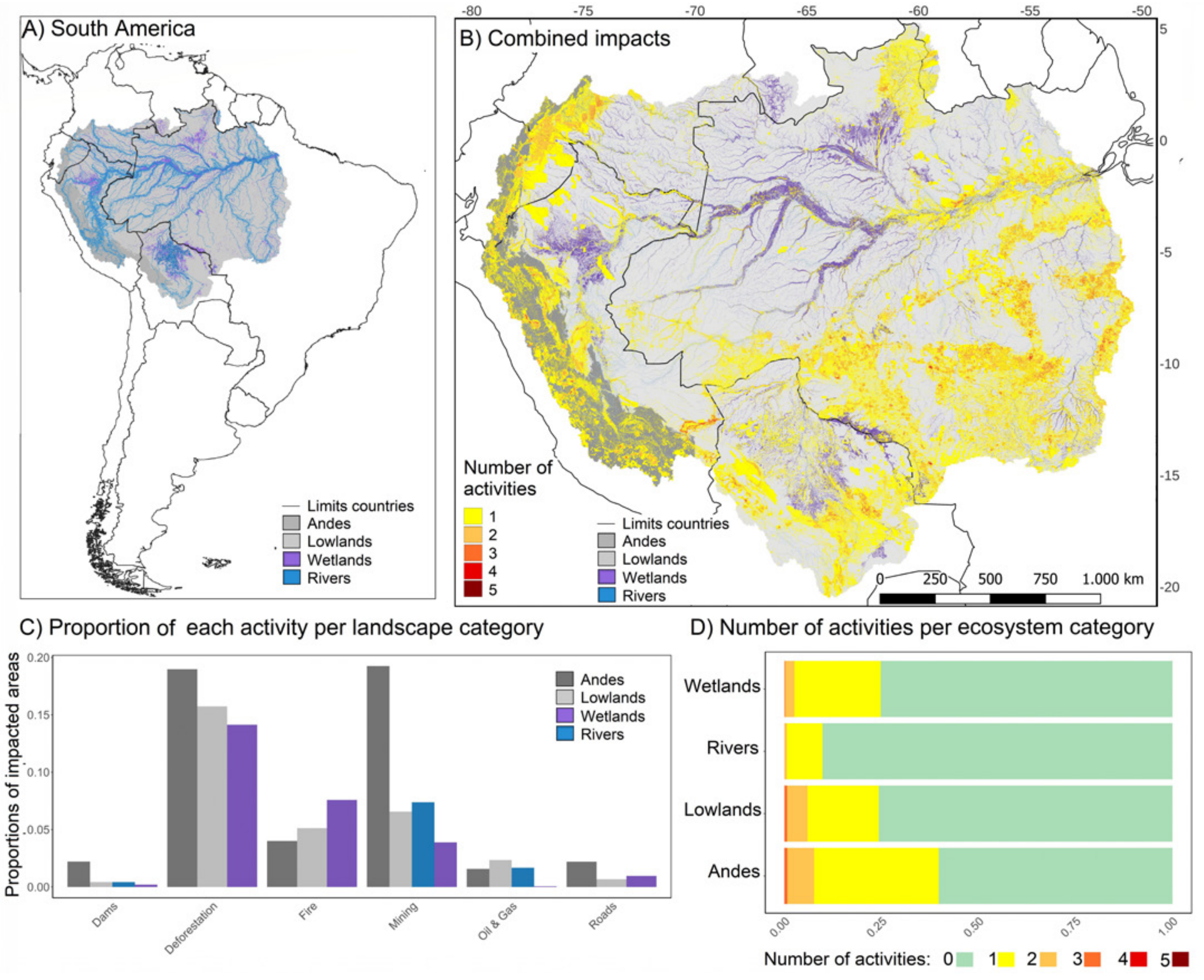


Figure 1. Anthropogenic impacts in the Amazonian Andes (dark gray), wetlands (purple), rivers (blue), and lowland terrestrial ecosystems, including rainforests and savannahs (light gray). **A)** The limits of the Amazon drainage basin. **B)** Combined impact of human activities. Colors denote the numbers of anthropogenic activities impacting an area: yellow (one activity), orange (two activities), light red (three activities), red (four activities), dark red (five activities). **C)** Proportion of area impacted by each of six anthropogenic activities in the Amazonian Andes (dark gray), lowland forests (light gray), wetlands (purple), and rivers (blue); **D)** Proportion of combined impact across the Andes, wetlands, rivers, and lowlands: green (zero activities), yellow (one activity), orange (two activities), light red (three activities), red (four activities), dark red (five activities).

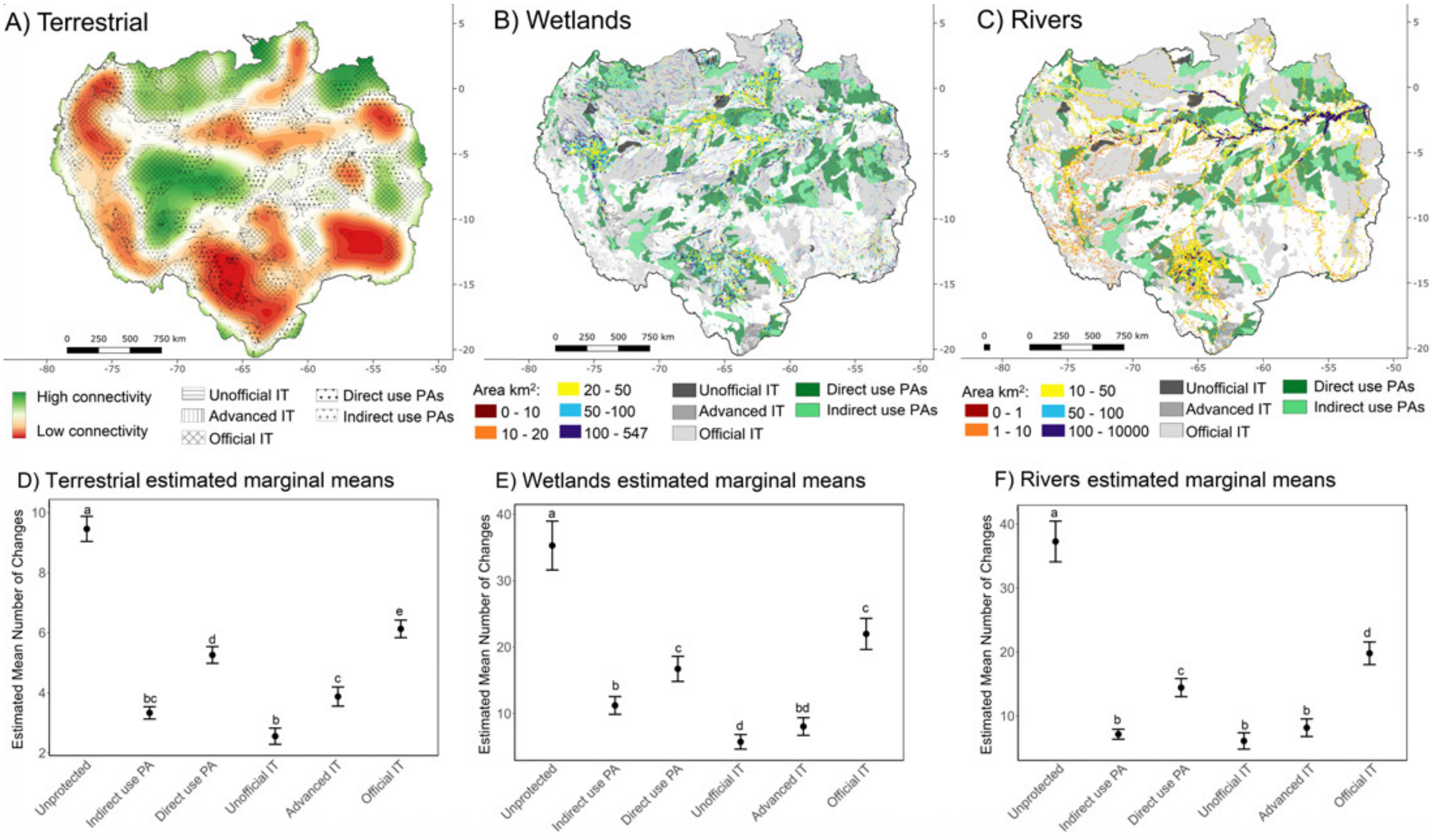


Figure 2. Ecosystem connectivity in the Amazon basin. **A)** Amazonian non-flooded areas (including tropical rainforests, white-sand ecosystems, and savannas) with kernel density connectivity map (see text); Indigenous Territories (ITs) and Protected Areas (PAs) are shown as polygons with different patterns. **B)** Amazonian wetlands (permanently and seasonally flooded areas) showing regions of the connected areas at threshold = 0, where large connected areas are shown in blue, small connected areas are shown in red, and intermediate in yellow; Indigenous Territories (ITs) and Protected Areas (PAs) are shown as polygons with different colors. **C)** Amazonian large rivers (Stream Orders 6–10) showing functionally connected areas, where large connected areas are shown in blue, small connected areas are in red, and intermediate areas in yellow; Indigenous Territories (ITs) and Protected Areas (PAs) are shown as polygons with different colors. Estimated marginal means for **D)** non-flooded terrestrial, **E)** wetland, and **F)** riverine ecosystem areas, showing the number of changes in connectivity across different protection categories: unprotected, indirect use PAs, direct use PAs, unofficial ITs, advanced ITs, and official ITs, with significant differences showed by small caps letters.

Ecosystem Connectivity

Ecosystem connectivity allows environmental flows of organisms, materials, and energy across ecosystems, supporting the integrity and functionality of natural systems, and the maintenance of biodiversity[25]. It is hence critical to the healthy functioning of population-level processes such as natural selection and gene flow, ecological-scale processes like competition and predation, and abiotic exchange such as water and nutrient flow and nutrient cycling. These ecological and evolutionary processes are themselves required for the long-term persistence of species and ecosystems[26–29].

Ecosystem disruption may increase the level of difficulty for an organism or process to naturally flow through the ecosystem. This depends on the spatial distance between target habitats or ecosystems, and the suitability of the intervening matrix. Here, we used habitat integrity to infer ecosystem connectivity, assuming that altered habitats pose resistance to both biotic and abiotic flows. Specifically, we employed connectivity analyses using resistance rasters, which represent how a landscape facilitates or impedes biotic and abiotic flows. Movement across a given area is influenced by the degree of ecosystem degradation and the presence of natural or human-made barriers (e.g., large rivers fragmenting terrestrial habitats or dams interrupting river flows). This approach allowed us to identify key areas for the maintenance of ecological processes across ecosystems.

Andes-Amazon Connectivity

Approximately one-quarter of the Amazon's have already suffered degradation due to industrial scale human activities, leading to significant habitat loss and fragmentation of ecological corridors throughout the basin[30]. A particularly urgent issue is the accelerating erosion of connectivity between the Andean Amazon and the adjacent lowland terrestrial areas, driven by deforestation, extractive industries, and infrastructure development, especially in the Andean foothills of Colombia, Ecuador, and Peru[143]. These transboundary zones, while still harboring relatively intact ecological linkages (**Figure 2**), are increasingly vulnerable to pressures such as weak law enforcement, limited cross-border governance, legal obstacles, and escalating threats from illicit activities including drug trafficking, illegal logging, mining, and overfishing[31].

Indigenous Territories and Protected Areas (ITPAs) maintain higher terrestrial connectivity, as opposed to non-protected areas where industrial-scale human activities have more significantly disrupted ecosystem integrity (Negative Binomial GLMM, AIC = 4274.1, log-likelihood = -2129.1; $p < 0.01$; **Figure 2D**). Importantly, the Amazon River itself acts as a natural barrier to forest connectivity, highlighting the heterogeneous spatial distribution of connectivity and habitat fragmentation across the Amazon basin. This natural barrier separates partially distinct biotas north and south of the river[32], meaning that maintaining connectivity on only one side is insufficient to preserve the basin's full ecological integrity. Moreover, because major riverine and wetland systems converge on the Amazon River, ensuring connectivity across both margins is essential for sustaining the ecological processes that support biodiversity and ecosystem resilience.

Wetlands are similarly affected by human activities, with connectivity losses linked to dams, deforestation, and fires. Although wetlands within ITPAs maintain significantly higher connectivity (Negative Binomial GLMM, AIC = 6501.4, log-likelihood = -3242.7, $p < 0.01$; **Figure 2E**), major wetland systems across the basin have become increasingly fragmented (**Figures 1C, 2B**). Higher-connectivity areas (blue polygons in **Figure 2B**) persist along major floodplain corridores such as the Juruá and Negro rivers, whereas lower-connectivity regions (red to yellow polygons) are concentrated in the southeastern Amazon, where anthropogenic pressures are more intense. The loss of connectivity in these wetlands and riparian corridors poses serious threats to both aquatic and terrestrial biodiversity, disrupting the ecological processes that sustain wetland health, making their protection and restoration an urgent priority. While large wetland systems still exist in western Amazonia (e.g., Peru and Bolivia), their high internal ecological variability can result in smaller patch sizes, reflecting natural patterns rather than human-induced fragmentation. Interpreting connectivity patterns must therefore consider underlying ecological heterogeneity across multiple spatial scales from local patches (1-10 km^2) to regional basins (100 - 10,000 km^2).

Riverine ecosystems are also heavily impacted by dams and in-stream mining, which compromise the connectivity between headwater and lowland sections of rivers (**Figures 3B, 3C**). Connectivity is consistently higher within ITPAs (Negative Binomial GLMM, AIC = 5415.2, log-likelihood = -2699.6, $p < 0.001$; **Figure 2E**), virtually all Andean rivers are severely impacted by dams and mining activities (**Figures 3B, 3C**). Among the major rivers originating in the Andes, only the Putumayo, Napo, Japurá, Madre de Dios, and Beni remain largely undammed (**Figure 3B**). However, the Madre de Dios and Beni are disconnected from the lower Madeira and Amazon rivers by two large (>10 MW) dams on the Madeira and the upper Napo is heavily impacted by pollution and overfishing associated with petroleum extraction and oil palm plantations[33,34]. The fragmentation and degradation of these waterways interrupts the flow of sediments, nutrients, and aquatic organisms, as well as aquatic productivity, all vital processes for maintaining riverine ecosystems[16]. Despite numerous dams in their upper reaches, the Marañón and Ucayali rivers maintain relatively high longitudinal connectivity in the lowland portions of the Amazon River (**Figure 3B**).

Global and regional climate change pose escalating threats to long-term biodiversity distribution, ecosystem functions, and connectivity across the Andean-Amazon axis. Shifts in temperature and precipitation regimes are pushing many species beyond their adaptive thresholds, undermining the stability of ecological processes[30]. In this context, maintaining and enhancing connectivity becomes increasingly vital, not only to support the continuity of hydrological and nutrient cycles, but also to enable

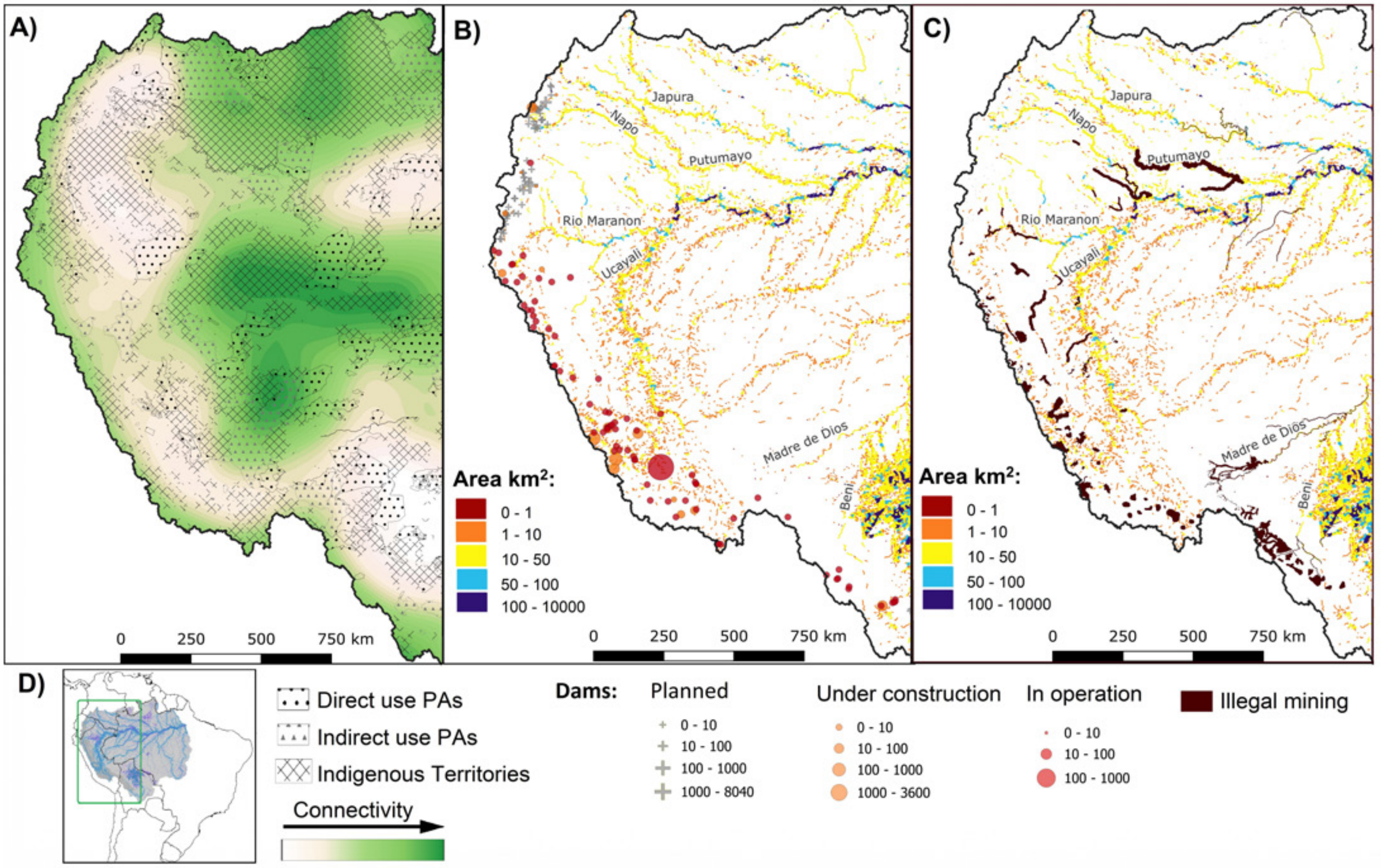


Figure 3. Connectivity of the Andes and western Amazonian lowlands. **A)** Areas of high terrestrial connectivity, highlighting the Indigenous Territories (crossing lines points) and Protected Areas (points and triangles). **B)** Areas in km^2 highlighting dams (sized by their potency in megawatts – MW) and major rivers that connect Amazon Andes to lowland yet free of dams. **C)** Areas in km^2 of connected rivers, illegal mining (dark red) and major rivers that connect Amazon Andes to lowland yet free of dams. Beni and Madre de Dios rivers are dam-free but have planned dams, and both drain to the Madeira River currently disrupted by two large dams. Marañon and Ucayali rivers are impacted by dams and illegal mining in their headwaters but represent two remaining rivers with connections between Central Andes and Amazon River. Large portions of the Napo basin (Coca River) is affected by the Coca-Codo Sinclair dam, but the southern portion of the basin is dam-free, yet with much illegal mining. We propose that these seven rivers be classified as protected *connectivity sanctuaries*, with a complete moratorium on construction of dams and water-diversion structures. **D)** South America map, highlighting areas shown in other panels.

elevational and longitudinal range shifts that allow plant and animal species to disperse, adapt, and persist under rapidly changing climatic conditions. Without functional ecological corridors, species may become confined to increasingly unsuitable habitats, increasing the risk of local extinctions and leading to the collapse of ecosystem functions essential to life-support systems at local, regional, and global scales[35,36].

The following section will provide more details regarding specific threats to connectivity in the Amazon, exploring how deforestation, mining, dam construction, and other human-induced disruptions undermine the integrity of this critical ecological network.

Threats to Ecosystem Connectivity in the Amazon

Amazonian ecosystems exhibit high habitat heterogeneity, and high measures of both alpha and beta diversity[37–39]. This heterogeneity is a key factor contributing for the connectivity between ecosystem exchanges allowing the resilience of the Amazon ecosystems. Ecosystem connectivity between the Andes and lowland Amazonia creates and maintains environments for a vast number of species[6,17,40]. By regulating geomorphological processes such as river meandering, sediment deposition, and floodplain formation, unimpeded river flows Andes-Amazon connectivity also ensure healthy ecosystem function[41]. However, predatory industrial scale activities are threatening these processes, affecting Amazonian ecosystems up to hundreds to thousands of times faster than natural processes[30]. Here we discuss in more detail each of the six major anthropogenic impacts in the Andes-Amazon region.

Dams: Dams represent one of the most challenging and serious impediments to connectivity in aquatic and seasonally flooded systems, also causing stream dewatering and downstream hydrological alterations, and affecting the entire river basin. These impacts extend over hundreds of kilometers from the reservoir, altering downstream flood regimes and impacting ecosystem dynamics and species composition[42–47]. Dams contribute to ecosystem loss and severe changes in hydrological regimes[45–47], hindering climate change mitigation due to the emission of carbon dioxide and methane from underwater biomass decomposition[10]. The environmental impacts of dams also include disturbances to river ecology and fragmentation, loss of aquatic and terrestrial biodiversity, and habitat destruction[48–52]. Dams impede sediments and nutrients from moving downstream, reducing the productivity of fishes, which are crucial for ecosystem health and local livelihoods[47,53]. They block fish migrations, such as the iconic catfish dorado, which travels 3,000 miles from the mouth to the headwaters of the Amazon River to spawn and is slowly disappearing as a result of damming[54,55]. Furthermore, interrupting river connectivity alters seasonal flood dynamics, reduces water quality, and increases the frequency and intensity of extreme weather events, compounding the overall ecological and social impacts of these hydroelectric projects. The construction of reservoirs and transmission lines leads to significant deforestation, but the impacts extend further: dam projects often attract large numbers of workers and associated infrastructure, and once construction is complete, many of these individuals remain in the region without employment. This post-construction demographic pressure frequently drives new waves of deforestation, as former workers turn to logging, land clearing, or small-scale mining, accelerating the degradation of surrounding ecosystems.

Our dataset includes 347 dams in operation in the Amazon basin in 2023, 85 dams under construction, and 397 more in planning stages[23, 143]. This number can be underestimated since Caldas et al.[56] identified 434 barriers built or under construction with 463 proposed or in the early planning phases. Many of these dams are being built or planned in the headwaters of the Amazon Basin in the Andes. Of the 96 long rivers (>500 km) in the Amazon, 73 were dam free in 2019, but just 51 will be dam free if all these projects are completed[56].

Although dam reservoirs cover just 4% of Amazonian Andes (**Figure 1**), they impact a disproportionately larger region due to the interruption of sediment, nutrient, species flows, and human demographic shifts. Amazonian dams have already resulted in profound changes in the community structure and functional traits of fish assemblages leading to a decline in fisheries both upstream and downstream of the dams. These changes propagate into other ecological systems, resulting in lost livelihoods and food provisions, the spread of diseases and territorial conflicts[47,57–59]. The existing network of Protected Areas in the Amazon basin seems poorly designed to preserve the biotic connectedness of aquatic ecosystems[60].

To maintain what remains of the Andes-Amazon connectivity, it is key to avoid building new large-capacity (≥10 MW) dams in Amazonian rivers[9]. Even the construction of dams with installed capacity <10 MW should be evaluated carefully because of their cumulative effect of blocking multiple tributaries[10]. In cases of dams with installed capacity <10 MW, which would power a single town or village, the rivers' flows must be considered, and proper environmental licensing and evaluation using risk-based approaches should be followed[10,61,62]. We further recommend maintaining the few rivers (and riverine vegetation) that currently lack dams —mainly the Japura, Putumayo-Iça, Beni, and Madre de Dios basins—, as well as the tributaries of the Marañón and Ucayali rivers that, despite the presence of multiple dams near their headwaters, serve as vital links connecting the central Andes with the Amazon River, to function as transboundary dam-free sanctuary for the Andes-Amazon aquatic connectivity (**Figure 3**). To achieve this *sanctuary* status, policymakers should consider creating specific protected area designations that prioritize the preservation of aquatic connectivity, such as Ramsar Sites or UNESCO Biosphere Reserves, which can provide an international recognition and protection framework. Succeeding in the establishment of these proposed sanctuaries requires a strong political commitment and agreements involving the governments of Brazil, Ecuador, Colombia, and Peru.

Other rivers that are key for long-distance migrating fishes, turtles and dolphins include the Amazon, Negro, Napo, Juruá, Preto do Igapó Açu, and Uraricoera rivers[56]. Efforts should also be directed towards maintaining (and restoring) connectivity along these rivers.

Deforestation: The removal of vegetation cover is the biggest threat to Amazonian ecosystems, fragmenting the landscapes and reducing connectivity. Deforestation closely interplays with other impacting activities because the drivers of deforestation include, among other factors, the opening of new roads, the construction of dams, the exploitation of minerals, oil, and gas, and the conversion of natural vegetation into pasture and croplands[8,10,63–65]. Deforestation has a wide spectrum of negative consequences, from local to global scales. Apart from loss of biodiversity and ecosystem connectivity, deforestation causes changes in local and regional regimes of temperature, precipitation, evapotranspiration, and streamflow, increasing the incidence of extreme hydrometeorological events and global carbon and other greenhouse gas emissions[22,66], and threatening human safety and well-being, especially of IPs and LCs[67].

As of 2020, a cumulative total of 14% of Amazonian wetlands, 19% of the Amazonian Andes, and 16% of lowland forests were deforested (**Figure 1**). Studies have shown that the area of degraded forests (those damaged by fragmentation, logging, or subcanopy wildfires) is 39% larger than the area of deforestation[68,69]. The region's most severely impacted by deforestation are on the southeastern edge and in the eastern portion of Amazonia in Brazil and Bolivia[143]. These areas have a history of governmental incentives for unsustainable rural development, fueled by forest exploitation and land use change[70,71]. Practices such as the slash-and-burn for big farms and monoculture are directly associated with aggressive deforestation[51]. The survival of the remaining forest patches depends on a significant political shift toward recognizing the importance of biodiversity and taking action to conserve and reconnect those remnants. Local forest dwellers can play a crucial role in this effort. IPs and LCs are known to effectively protect biodiversity[72] and most of the areas occupied by Indigenous peoples in the Amazon are forested[73].

Formal recognition of Indigenous Territories and the expansion of Protected Areas are central strategies for avoiding deforestation and maintaining ecosystem connectivity in the Amazon. These efforts must be accompanied by technical and financial support to strengthen Indigenous Peoples (IPs) and Local Communities' (LCs) territorial management and protection strategies. We join the call to align these actions with international conservation commitments, including the 30x30 target of the Kunming-Montreal Global Biodiversity Framework (https://www.cbd.int/gbf) and the Amazon-specific 80x25 goal, which aim to safeguard at least 80% of the Amazon by 2025 through Indigenous and protected land governance.

Additionally, ecosystem restoration must be prioritized as a complementary action to conservation[74,75]. In line with the UN Decade on Ecosystem Restoration (https://www.unwater.org/news/united-nations-general-assembly-declare-2021-2030-un-decade-ecosystem-restoration), we support the implementation of Arcs of Restoration as proposed by Barlow et al.[74], particularly in the deforestation frontiers of southern and southeastern Amazonia in Brazil and Bolivia, and the Andean foothills of Colombia, Ecuador, and Peru. These targeted restoration initiatives are essential to recover lost forest cover, reestablish ecological functions, and buffer against future environmental degradation.

Wildfires: The increasingly higher numbers and magnitude of fires in the Amazon are worrisome. In the last 18 years, an average area of >151,000 km² of the Amazon was burned annually[76]. Fire is not part of Amazonian rainforest natural dynamics and is mostly associated with anthropogenic activities[77]. As an unnatural occurrence, fires damage ecosystems that are not resilient to them.

Fires in the Amazon are closely related to deforestation, being used to clear areas for agro-pastoral use[78–82]. However, broad terms such as "aggressive deforestation" often obscure the specific drivers behind these fires. In countries with significant forest loss and remaining contiguous forest cover, such as Bolivia, fires have been directly associated with the expansion of monocultures like soy and speculative land appropriation, especially in ecologically sensitive areas like the Chiquitano dry forests. In many other regions, including Brazil, large-scale cattle ranching and mechanized agriculture continue to be major contributors to deforestation and associated fire outbreaks[83].

Deforested and degraded areas are also more susceptible to fires, a linkage that can be observed in our maps: fires were more frequent in the Brazilian Shield eco-geological region of the lowland forests and Amazonian wetlands[143]. The increased frequency, duration, and intensity of droughts also increase the likelihood of fires in the Amazon and vice-versa, in devastating feedback loop[76,77,84]. Addressing this challenge requires coordinated action among government, NGOs, local communities, and the scientific community with a focus on preventive strategies such as improved enforcement of environmental regulations, deterrents to illegal burning, stronger institutional coordination, and greater investment in fire monitoring, early warning, and response systems[85].

Mining: The Amazon has long been known as an area of high potential for mineral resources and represents one of the last mineral exploitation frontiers in the world[86]. Most legal mining is conducted by large international corporations[63], and it is largely export-oriented, generating significant environmental and social damage locally that disrupt the connectivity. However, the economic benefits of these ventures are often concentrated elsewhere, with limited reinvestment in local development or conservation. These dynamics are driven not only by local governance gaps but also by consumer demand in wealthy nations and permissive regulatory frameworks in importing countries. The absence of binding international accountability mechanisms and the lack of traceability in global supply chains allow corporations to profit from extractive activities without assuming responsibility for their ecological or social consequences.

Although the geographical extent of mining is usually smaller than the area of the concession, the mineral exploration requires roads and sometimes airstrips, drilling or trenching, processing and refining plants, waste disposal, and intensive water, energy, and reagent use[87,88], making the impact level much more extensive than the mined area *per se*. The damage is even more notable when contamination includes minerals that when consumed are noxious for the aquatic biota (e.g., bauxite, copper, and iron ore[89]) and humans. Furthermore, the lack of monitoring has already resulted in catastrophic environmental situations in South America, severely degrading human health and welfare[90–92].

Illegal mining is even more complex because it inherently despises all environmental regulation. It can occur in Protected Areas and/or Indigenous Territories, risking the lives of local people both through direct violence and the widespread and uncontrolled use of mercury[92–94], which has strongly impacted aquatic and semi-aquatic biota, and human health89. While mercury contamination is a critical concern, the broader environmental impacts of gold mining, particularly mechanized forms involving dredges and heavy machinery, deserve further attention in proportion to the scale of their effects on Amazonian freshwater systems and IPs and LCs. Recent studies identify gold mining as the main threat to the rivers in tropical America, due to its far-reaching impacts on physical and chemical properties of aquatic ecosystems[95]. These include not only mercury pollution, but also increased sediment loads, disruption of flow regimes, destruction of aquatic habitats, and alterations in underwater light fields, which affect primary production and trophic dynamics.

In Brazil, this threat skyrocketed after political support from the 2019–2022 Federal Administration, which euphemistically used the term artisanal mining to legalize small-scale illegal mining and enable its implementation without commitment to rehabilitate degraded areas[96], which fortunately was revoked by the new government[97]. In Ecuador, not only mining concessions have dramatically increased since 2016[98], but extraction is tightly interlinked with violence and delinquency[99].

Large areas of eastern Amazon are currently being explored for mineral resources[143], including Protected Areas and Indigenous Territories (**Figure 1**). Both legal and illegal mining exploitation has recently advanced to new frontiers in northern and central Amazon[100], with 45,065 mining-prospection concessions or concessions waiting for approval, 21,536 of which overlap with Protected Areas[23,92,100]. Activities with potentially high environmental impact, such as mining, oil extraction, and large-scale agriculture and livestock farming, must be subject to rigorous environmental licensing processes. These processes should include comprehensive and independent environmental impact assessments, conducted in partnership with IPs and LCs, and with the involvement of Amazon-based institutions such as universities, research centers, and NGOs.

Crucially, these assessments must respect the right to Free, Prior, and Informed Consent (FPIC), as established by ILO Convention 169, the UN Declaration on the Rights of Indigenous Peoples, and UN Human Rights Council Resolution 39/12. Transparency in commodity supply chains originating in the Amazon is equally essential. Public disclosure of sourcing, environmental, and social safeguards should be mandatory, ensuring accountability and enabling consumers and other stakeholders to make informed decisions.

Areas impacted by mining must be restored with funding from mining companies but executed by local communities and independent research centers or universities[101]. Stopping illegal mining is a much more complex but urgent endeavor, requiring community engagement and the direct and committed involvement of governments[102,103].

Oil and gas exploitation: Oil and gas exploitation occurs mainly in western Amazon, within and around the Andes (**Figure 1**). These activities increase deforestation through road and pipeline construction[104,105], land cover changes, ecosystem fragmentation, and surface and underground water contamination[106]. Oil spills pose an additional risk, having occurred numerous times in Colombia, Ecuador, and Peru[107,108]. Although the impacts of oil spills on aquatic biodiversity and human health are massive, the damages usually remain unrepaired, as exemplified in the Texaco/Chevron case in Ecuador[109].

Many areas (>36,000 km^2) under oil and gas exploitation/exploration are in Protected Areas or Indigenous Territories (**Figure 1**); more than 16,000 km^2 have been solicited by companies and more than 72,000 km^2 recognized as potential areas for future exploration/exploitation[23]. We recommend prohibiting oil and gas exploitation in Protected Areas. IPs and LCs must be consulted for any new project within their lands as previously explicit in the mining section. Ongoing projects should include mandatory independent monitoring of activities, and the observation of the Oil and Gas industry guidelines for drilling in vulnerable ecosystems are also imperative (IPIECA; https://www.ipieca.org/). Also, in the context of the climatic crises a serious policy of decarbonization, including a reduction of fossil fuel exploitation, is a necessary step for all countries in the Amazon basin. This shift is not only important for the countries themselves but for the entire world, as much of the fossil fuel extracted is for export. However, for countries heavily reliant on fossil fuel revenues, which can represent a significant portion of their GDP, this transition poses economic challenges. Managing the reduction of revenue from fossil fuel exports requires innovative policies. For example, Colombia's carbon tax, though not aimed at eliminating fossil fuel exploitation, is a step in the direction of taxing carbon emissions and could serve as a model to explore for balancing environmental goals with economic realities.

Roads: Roads constitute one of the main causes of deforestation in the Amazon[110–112]. Highways spawn networks of roads, known as the fishbone deforestation pattern[113], leading to uncontrolled human migration, invasions, and new settlements[71,113,114]. Several Brazilian Amazonian highways, such as the Trans-Amazonian Highway (BR-230), BR-163, and BR-319 are still in the process of improvement and paving, which raises concerns about their environmental and socio-economic impacts[115].

Roads facilitate ecosystem degradation[61,110], a pattern that is also evident in the Amazon basin[143]. We recommend avoiding road construction in areas where ecosystems are still minimally impacted, and particularly within ITPAs. To support communities that need access to essential services such as food and healthcare, alternative solutions such as enhanced river transport systems could be implemented. Policies could include equipping boats with mobile health systems to serve remote areas, ensuring access to vital services while protecting ecosystems. Main roads already built in Protected Areas should have permanent monitoring to prevent the construction of secondary roads and to avoid the illegal extraction and transport of wood and other products.

The Critical Role of Indigenous Territories and Protected Areas for Andes-Amazon Connectivity

Across all ecosystems, our results confirm[116–122] that the percentages of ecosystem disruption are lower in Indigenous Territories (14%) and Protected Areas (16%) relative to other areas (38%). Recognition and demarcation to support effective management and funding of Indigenous Territories, along with the creation of new Protected Areas are essential. For example, there are 560,000 km² of non-allocated public lands ("*terras devolutas*") in the Brazilian Amazon. The federal government plans to title these lands for Indigenous Territories and establish new Protected Areas. Protected Areas with local communities and Indigenous Territories are key to maintaining Andes-Amazon connectivity and should be central to ensuring a connected and healthy Amazon[123] (**Figure 1**).

When comparing connectivity within Indigenous Territories, Protected Areas, and non-protected areas in the different environments, the ITPAs have significantly higher connectivity than areas with no protection (**Figure 2**). Also, it is clear that Protected Areas have a positive impact on conservation; deforestation rates within Protected Areas were 1.6 (2002–2016) to ten times (2000–2017) lower than those in non-Protected Areas[119,124,125], while Indigenous Territories lost forests between 4.85 (year 1985) and 13 times (year 2000) less than adjacent non-Indigenous Territories[118,121]. Protected Areas account for 18% of Amazonian Andes, 24% of Amazonian lowlands, 25% of wetlands, and 18% of rivers, while Indigenous Territories account for 30% of Amazonian Andes, 33% of Amazonian lowlands, 24% of wetlands, and 20% of rivers (**Figure 1**).

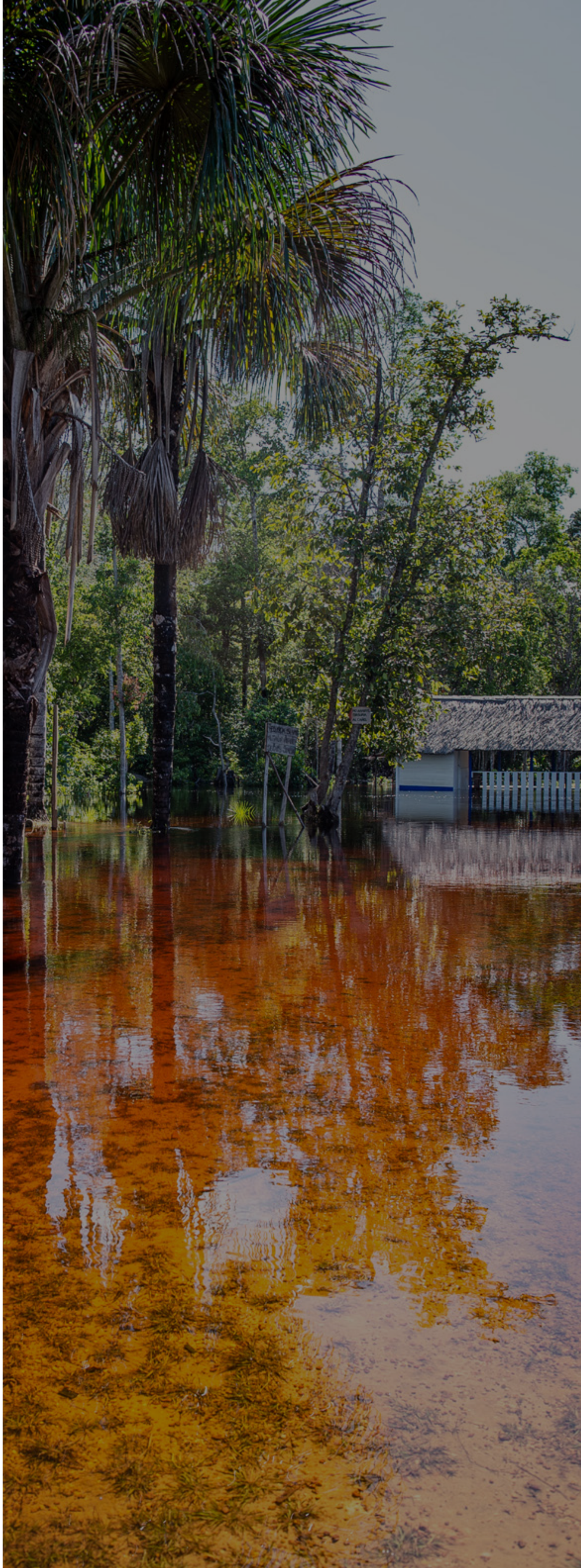
Together, ITPAs already cover nearly half of the Amazon basin, yet, a large portion of its ecosystems still remains unprotected. The creation of new Protected Areas or the official demarcation of Indigenous Territories, while essential, can be time-consuming, politically complex, or unfeasible in regions where traditional peoples already live and manage the land. Although sustainable use reserves present one possible solution, their implementation requires institutional support and long-term resources. In this context, Other Effective Area-Based Conservation Measures (OECMs) emerge as a valuable alternative, offering a promising pathway for enhancing connectivity and supporting traditional territories, including locally managed initiatives such as fishing agreements and Terms of Authorization for Sustainable Use. These mechanisms foster collaboration between local communities and governing bodies, providing more adaptive and inclusive conservation approaches. OECMs can also attract incentives and investments that empower local communities to achieve their conservation goals. At the same time, strengthening the legal recognition of Indigenous Territories and expanding inclusive forms of Protected Areas remains essential. These strategies, in concert with OECMs, help reinforce the central role of local populations and are key to sustaining the ecological and cultural resilience of Amazonian socioecological systems. Much of Indigenous Territories and Protected Areas are under pressure from agribusiness and illegal activities. Additionally, changes in laws and policies can greatly increase threats to these areas[116]. For instance, in Brazil, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAM)[126,127], which was implemented in 2004, reduced deforestation; it was interrupted in 2019, but returned in 2023[97]. Furthermore, recent laws in Brazil allowed more economic activities within Indigenous Territories and reduced the governance within Protected Areas[128]. These laws are being reversed now with the new government, but reestablishing governance in some areas as well as reverting the impacts of the last years will be a challenging task. Economic pressures, however, continuously influence legislation; during May 2023, Brazil's lower house of Congress approved regulations that limit the recognition of new Indigenous Territories, which can now only be established if indigenous people can prove they occupied the land by 1988, the year when the current Brazilian constitution was promulgated. This new bill, which was considered unconstitutional by the Brazilian Supreme Court but, even so, was approved by the Senate, is an obvious setback to Indigenous communities, which had been excluded from their ancestral territories in the 1970s and 1980s[129].

Although our analysis shows that areas of integral protection (e.g., National Parks and Biological Reserves) exhibit high levels of connectivity, it is important to recognize that many of these areas are located in regions of comparatively low anthropogenic pressure, which may partially explain their current levels of ecological integrity. The imposition of conservation models that exclude traditional populations can result in severe social injustices and erode the long-term stewardship that is essential for sustaining these ecosystems. Furthermore, the contribution of ITPAs goes beyond formal legal status. Their effectiveness is deeply rooted in the daily practices, traditional knowledge, and political resistance of IPLCs, who serve as frontline defenders of these landscapes[130]. Through rotational agriculture, controlled burning, sacred sites, and customary norms, IPs and LCs maintain dynamic cultural landscapes that support ecological connectivity and prevent deforestation[117,131]. It is often their collective action that halts illegal activities and resists degradation, even under intense external pressure. Recognizing and supporting these efforts is not only a matter of justice, but also of ecological necessity.

For instance, Indigenous Territories and areas managed by traditional communities, such as Brazil's RESEX (Extractive Reserves), significantly reduce forest loss and effectively control illegal activities[116,118,119,121,126,127]. Empowering these communities through sustainable bioeconomy initiatives not only enhances their quality of life but also strengthens conservation efforts.

Likewise, the effective management of ITPAs requires sustained funding, law enforcement, and stronger legal frameworks. Prioritizing these areas through improved governance can ensure long-term conservation, while promoting a transparent, sustainable bioeconomy offers a win-win scenario for biodiversity conservation and local communities' well-being[132].

Economic activities threaten currently recognized Protected Areas and Indigenous Territories, mainly in the southern Amazon basin (**Figure 2**). We quantified more than 27,000 km^2 with at least one impacting activity in Protected Areas and 178,000 km^2 in Indigenous Territories (**Figure 1**). Existing ITPAs, in conjunction, form a promising scheme for ensuring connectivity, but appropriate funding and management plans and law enforcement are crucial to enforce the protection in practice. Examples of community governance systems that use forest resources both for subsistence and commercial markets, while conserving forest and aquatic systems function, already exist in the Amazon (e.g., the management of *Arapaima gigas* along the Juruá and Upper Amazon rivers[72,133]). Securing and expanding collaborative partnerships to maintain and recover fisheries and floodplain ecosystems should be a priority[134,135]. Also, forest conservation initiatives are also happening, such as the project Corazon de la Amazonia conservation agreements with farmers in Colombia[136]. The fastest, most efficient, and cost-effective strategy to conserve the Amazon is to ensure effective governance by placing IPs and LCs at the center of decision-making for their lands, inhibiting illegal activities, and respecting their lifestyle promoting a standing forests and flowing rivers sociobioeconomy.



Conclusions

Connectivity in the Amazon basin is crucial for maintaining both aquatic and terrestrial habitats. ITPAs form the backbone of this connectivity, but they are under increasing pressure and need greater support to remain effective. While deforestation and other activities are often legally restricted in these areas, illegal activities still pose significant threats. Our analysis of the six major impacts (dams, deforestation, fires, mining, oil and gas exploitation, and roads) highlights where connectivity must be strengthened, either through the creation of new Protected Areas (PAs) or Indigenous Territories (ITs), restoration efforts, or other mechanisms of protection. To address these challenges, it is essential to adopt a governance approach that empowers IPs and LCs to enhance their role as guardians of the Amazon and strong alliance with governments across the basin. This includes improving their livelihoods and well-being through sociobioeconomy initiatives and other sustainable solutions.

In parallel, we identify rivers *sanctuaries* that need protection to maintain riverscape connectivity within the Amazon basin. Our analyses identify the Japurá, Putumayo, Beni, and Madre de Dios rivers as such *connectivity sanctuaries*, which should also include nearby riverine ecosystems to maintain functional land/water dynamics.

We also highlight that large areas that connect the Andes-Amazon ecosystems have been altered at some level, including a total of 23% of lowlands, 24% of rivers, 25% of wetlands, and 28% of the Amazonian Andes. In this context, action is needed to conserve the areas that remain with high connectivity (**Figure 3**). Based on our connectivity analysis, we suggest the following corridors to maintain the terrestrial Andean-Amazonian transition: (i) a northern/Colombian corridor, connecting the Serranía de los Churumbelos, Alto Fragua Indi Wasi, La Paya, Sierra de Chiribiquete, Yaigojé Apoporis, Cahuinarí, Río Puré, and Amacayacu. (ii) A southern corridor, to connect Protected Areas and Indigenous territories of Peru, including Alto Purus, Manu, Apurímac, and Amarakaeri. (iii) In Ecuador, an additional corridor, although hampered by oil concessions, should be established to connect the Cayambe-Coca, Sumaco, and Yasuní National Parks.

Simultaneously, we recommend restoration initiatives across the basin to promote landscape connectivity between the Andes and the Amazon, and to limit continued Amazonian degradation and destruction[74,75]. These restoration efforts should aim to recover ecosystem function, connectivity, and biodiversity in impacted areas. Initiatives from the United Nations' Restoration Decade could benefit these efforts. Restoration should go, hand-to-hand, with socially just and sustainable economic activities[74].

Since anthropogenic activities are heterogeneously distributed in Amazonian ecosystems (**Figure 1**), a "one-fits-all" conservation plan is not an appropriate strategy for the region. Accounting for human occupancy patterns is crucial to protect and guarantee conservation goals. For example, the areas with local communities may be recognized under, for instance, the Sustainable Use Protected Areas (such as the Sustainable Development Reserves of Brazil), which allow local communities to maintain their livelihoods within largely intact ecosystems[137]. Indigenous Peoples play a crucial and immeasurable role in controlling deforestation, maintaining biodiversity, reducing forest carbon emissions, and mitigating climate change. Our study shows that Indigenous Territories and Protected Areas currently connect the main ecosystems in the Amazon basin. However, ensuring long-term biodiversity and connectivity requires not only respecting and supporting these areas but also involving other traditional communities, such as *campesinos* (small farmers), *ribeirinhos* (riverside dwelers), and *quilombolas* (Afro-Brazilian descendants of enslaved peoples who established independent communities known as quilombo). Their participation is essential for maintaining and restoring connectivity, preventing deforestation, and curbing illegal activities like mining. Recommendations and support for these communities are equally important to ensure connectivity across the entire region.

Material and Methods

This white paper synthesizes spatial analyses of human-induced impacts across the Amazon Basin, focusing on four ecologically distinct landscapes: the Amazonian Andes, lowland forests, wetlands, and river systems. The definitions and criteria used in the spatial delineation are consistent with those described in detail by Ritter et al (2025)[143].

To define the study area, we used the wetlands map produced by the Large-Scale Biosphere-Atmosphere Experiment (LBA)[2]. Elevation thresholds were applied to distinguish terrestrial zones: areas above 600 meters were classified as part of the Tropical Andes, and those below 600 meters as lowland rainforests[24]. Wetlands included seasonally flooded forests, swamps, and estuaries, while large rivers were identified using Strahler stream orders 6 to 10 from the HydroRivers database[138].

We overlaid layers of Indigenous Territories and Protected Areas (ITPAs) from the RAISG database[23], categorizing them according to land use permissions and legal status. These categories included direct-use protected areas (e.g., extractive reserves), indirect-use areas (e.g., national parks), officially recognized Indigenous Territories, areas with indigenous presence lacking legal recognition, and territories in the process of official recognition. In cases of spatial overlap between categories, the more protective designation was prioritized.

To assess ecological connectivity, defined here as the extent to which natural processes can proceed uninterrupted across ecosystems, we grouped the Andes and lowlands as a single terrestrial unit, resulting in three focal ecosystem types: terrestrial environments, wetlands, and river systems.

We developed resistance rasters to represent barriers to connectivity, where lower values indicate higher ecological permeability. These rasters were constructed using cumulative impact scores for deforestation, fire, mining, oil and gas extraction, roads, and dams, all available from RAISg (Table S1). Fire data were derived from annual rasters of burn scars provided by RAISG, spanning the period from 2016 to 2021, with a spatial resolution of ~30 meters. All data were harmonized to a common spatial resolution of 180 meters and incorporated each weighted according to empirical data from the Napo River basin, which linked these activities to changes in aquatic communities, habitat integrity, and water quality. Impact values were calibrated by ecosystem[139]; for instance, dams imposed high resistance in riverine systems but little in terrestrial ones.

Resistance values were assigned to each pixel by summing the weighted impacts of overlapping human activities. We also incorporated natural features—such as large rivers—that inherently limit species movement in terrestrial settings. Including both anthropogenic and natural barriers allowed for a more comprehensive understanding of constraints to ecological functionality.

Using these resistance surfaces, we delineated patches of functional connectivity—areas where resistance fell below defined thresholds. The size and shape of these patches reflect the level of connectivity, with larger and more cohesive patches representing higher integrity. Connectivity analyses were conducted using the 'grainscape' R package v.0.4.4[140], which employs lattice-based graph theory to quantify spatial structure. For terrestrial zones, regularly spaced focal points were used; for wetlands and rivers, random sampling was applied to select focal areas.

Threshold values for delineating connected patches were derived from scalar analyses examining the relationship between the number of patches and resistance thresholds. For terrestrial and riverine systems, the optimal threshold was identified using the maximum curvature (second derivative) of the response curve. For wetlands, a conservative zero-resistance threshold was adopted due to the binary behavior of the curve.

To map and visualize connectivity, we applied kernel density analysis to terrestrial polygon centroids (with higher density implying lower connectivity), and color gradients to represent polygon sizes in wetlands and rivers.

To evaluate the influence of ITPAs on ecological connectivity, we overlaid connectivity patches on a regular grid (cell size ≈200 km²), comparing the number of distinct patches within each protection category. Fewer patches within a given cell indicate higher connectivity. We modeled these patterns using a generalized linear mixed model (GLMM) with a negative binomial distribution, treating the ITPA category as the predictor and grid cell ID as a random effect to account for spatial autocorrelation. Post-hoc comparisons were performed to identify significant differences among categories.
Model performance was evaluated using pseudo-R^2 estimates based on the trigamma method. Sensitivity analyses were also conducted by varying resistance weights ±10–50%, confirming the robustness of connectivity metrics across scenarios. All spatial data processing and analysis were conducted using R v4.2.2[141] and QGIS[142], and the complete dataset and code are publicly available at: http://doi.org/10.6084/m9.figshare.28089815.

	Land	Rivers	Wetlands
Land	-	Inf (=NA)	100
Rivers	6	-	2
Wetlands	6	2	-
Large dams (>=10MW)	3	12	10
Large dams under construction	2	5	3
Small dams (<10MW)	2	10	7
Deforestation	7	-	7
Fires	7	-	12
Mining exploitation	7	7	7
Mining concession	3	3	3
Illegal mining	7	7	7
Oil exploitation	4	4	4
Roads	6	6	6

Table S1. Impact values for each human impact and focal ecosystems.

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