Connectivity in the Amazon basin: The critical role of Indigenous Territories and Protected Areas

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Key Messages

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

(ii) The Amazon basin is currently experiencing more rapid deforestation and degradation 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) Different landscapes are under varied pressures: wetlands and savannas are affected mostly by fire, Andean rivers by dams and mining, and terrestrial lowlands by deforestation. Dams and illegal mining, mostly in the Andes, are the main factors disrupting aquatic connectivity.

(iv) Primary anthropogenic impacts are driven by the elimination or weakening of governmental controls and environmental policies, insufficient environmental legislation, and the explicit impunity and social violence of violators who conduct illegal activities. As of 2020, 23% of the lowlands, 24% of the rivers, 25% of the wetlands, and 28% of the Amazonian Andes were under at least one human activity impact. Most of these changes took place in the last 40 years. Areas of greatest concern are summarized in Figure 1, and 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 Basin) and Protected Areas (~25% of the Amazon Basin) is the most important and viable way to maintain aquatic and terrestrial habitat connectivity in the Amazon basin.

Recommendations

(i) To effectively protect Amazonian biodiversity and ecosystem functionality, including those dependent on Andes-Amazon connectivity, it is imperative to strengthen and reestablish effective governance in Indigenous territories and protected areas.

(ii) We recommend establishing “dam-free” sanctuary zones to perpetuate the Andes-Amazon connectivity. We propose the Japurá, Putumayo, Beni, and Madre de Dios rivers as such connectivity sanctuaries, which should also include nearby riverine ecosystems, as a mean to maintain water-land dynamics.

(iii) We suggest the following corridors to maintain the terrestrial Andean-Amazonian transition: (a) a northern/Colombian corridor, connecting the Serranía de los Churumbelos, Alto Fragua Indi Wasi, La Paya, Sierra de Chiribiquete, Yaigojé Apoporis, Cahuinarí, Rio Puré, and Amacayacu. (b) A southern corridor, to connect Protected Areas and Indigenous territories of Peru, including Alto Purus, Manu, Apurimac, and Amara kaeri. In Ecuador, an additional corridor, although hampered by oil concessions, should be established to connect the Cayambe-Coca, Sumaco, and Yasuní National Parks.

(iii) Governance and coordination between Amazonian countries are essential for protecting the Amazon at the basin scale. Rapid enforcement mechanisms must necessarily include regional alert observatories, a robust legal framework, and prompt sanctions for violators.

(iv) In planning the economic development in the basin, we advise applying the Precautionary
Principle¹, emphasizing caution, deliberation, and review before starting large-scale projects. We recommend suspending all new dams that obstruct or divert waterways in the basin.

(v) Activities with potentially-high environmental impact, such as mining, oil drilling, and agriculture and livestock farming (e.g., IPIECA; https://www.ipieca.org/) should be monitored by independent institutions based in the Amazon region (e.g., universities, research institutes, NGOs).

(vi) Abolish in-stream mining operations in all waterways throughout the Amazon. At the same time, develop restoration and remediation management plans to recover areas that have been affected by extractive activities.

(vii) Conservation strategies must acknowledge and safeguard connectivity across the many ecosystems within the basin (e.g., wetlands, terrestrial, aquatic), naturally open areas, and riverine landscapes²,³), accounting for ecosystem heterogeneity and IPLCs cultural diversity.

Executive Summary

Preserving landscape connectivity across the Amazon basin, including the Andes/Amazon gradient, is critical for maintaining ecosystem functionality, biodiversity, and human well-being.

To identify areas with the highest importance for ecosystem connectivity in the Amazon Basin, we utilized satellite data to map human activities disrupting connectivity, such as dams and deforestation. Our analysis revealed widespread anthropogenic impacts affecting approximately 25% of all ecosystems. Notably, Indigenous Territories and Protected Areas emerged as crucial for maintaining connectivity across terrestrial, seasonally flooded, and aquatic ecosystems in the basin.

Strengthening protection measures for Indigenous Territories and Protected Areas will not only safeguard the Amazon’s ecological functions but also contribute to local community well-being, regional stability, and global biodiversity conservation. It ensures that the interconnected web of ecosystems continues to thrive, benefiting both nature and humanity.

Complementary, we propose the Japurá, Putumayo, Beni, and Madre de Dios rivers (and their associated riverine lands) as sanctuaries to perpetuate the Andes-Amazon connectivity. These rivers are some of the few remaining “dam-free” aquatic systems and should be the focus of regional, articulated conservation efforts to maintain their ecological integrity, dynamics, and connectivity.

Background

The Amazon Basin⁴ is a globally geodiverse and biodiverse region²,⁵,⁶, now severely threatened by numerous anthropogenic impacts⁷–⁹. These impacts act synergistically and, for the first time in human history, we face a scenario where the services related to water, nutrient and biodiversity resources provided by Amazonian ecosystems might functionally collapse¹⁰. This scenario is threatened by the synergistic combination of local land use changes and global climate change driven by human activities¹⁰. Among these risks, loss of ecosystem connectivity (i.e., degree of interaction and exchange of energy, materials, and ecological processes between distinct habitats or ecosystems within a larger landscape) due to landscape destruction poses the greatest environmental threats.

The Tropical Andes and Lowland Amazon constitute a two-way coupled system whereby the lowlands export water vapor that feeds rainfall in the Tropical Andes through aerial rivers, while the Tropical Andes export surface waters to the lowlands³,¹¹. Many rivers in the Amazon basin
originates in the Andes. 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\textsuperscript{11}. Furthermore, the Tropical Andes and Amazonian lowland ecosystems share a complex and intertwined evolutionary history that spans tens of millions of years\textsuperscript{5,6,12} 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 Amazonia being home to at least 10\% of global biodiversity\textsuperscript{13}, with numerous species still unknown to science, and a high endemism\textsuperscript{14,15}.

Maintaining landscape connectivity (here defined as the degree to which natural processes can occur unimpeded within an area) 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 and safety at the local, regional, and global levels. To establish priority areas for Amazonian preservation, it is imperative to incorporate the concept of maintaining connectivity at their core. Without the broader concept of connectivity, small reserves are destined to lose their biodiversity and functions\textsuperscript{8,10}.

In order to determine areas with highest importance for ecosystem connectivity at the Amazon Basin scale, we mapped the major human activities that disrupt connectivity, such as dams and deforestation, using satellite data\textsuperscript{16}. We demonstrate widespread anthropogenic impacts on Amazonia, affecting about 25\% of all ecosystems and disrupting connectivity in a heterogeneous fashion. Through a novel ecosystem-specific analysis, we assessed connectivity patterns in the basin. We found major disruptions, especially in aquatic ecosystems, but demonstrate that Indigenous Territories and Protected Areas (ITPAs) maintain connectivity of terrestrial, seasonally flooded, and aquatic ecosystems across the Amazon basin\textsuperscript{17}. This approach provides valuable insights for effectively managing and protecting the connectivity of the Amazon Basin, ensuring the preservation of its vital ecological functions.

**Landscape connectivity**

*Landscape connectivity* allows *Environmental flows* of organisms, materials, and energy across landscapes, supporting the integrity and functionality of natural ecosystems, and the maintenance of biodiversity\textsuperscript{18}. Thus, *landscape connectivity* is critical to the healthy function of population-level processes like 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\textsuperscript{14,15,19,20}.

Ecosystem disruption may increase the level of difficulty of an organism or process to flow through the landscape. This depends on how far an ecosystem is apart from each other and/or the permeability of surround matrix. Herein, we focused on ecosystem integrity as a proxy for inferring ecosystem connectivity, and we assume that degraded lands pose resistance to both biotic and abiotic flows. Ecosystem fragmentation, which increases the level of difficulty of an organism or process to flow through the landscape, is one of the main drivers of population reductions and loss of genetic variability\textsuperscript{21}. *Connectivity* modeling allows researchers to quantify landscape connectivity and is widely used in conservation planning\textsuperscript{22}. Resistance can be considered the basis of connectivity analyses, which indicates the degree that a landscape difficult or facilitate the biotic and abiotic movements across a given landscape being influenced by the degree of ecosystem degradation combined with the existence of natural or
anthropic barriers (e.g., large rivers in terrestrial landscapes or large dams in a river). This approach allowed us to identify areas important for movement of organisms and maintain ecological processes across different ecosystems, which is important for conserving biodiversity and ecosystem functionality.

To quantify the proportion of impacted areas, and to map the impacts, data for six major anthropogenic activities affecting the functionality of Amazon ecosystem as of 2020 was compiled: dams\textsuperscript{16}, deforestation\textsuperscript{16}, fires\textsuperscript{16}, mining\textsuperscript{16}, oil and gas exploitation\textsuperscript{16}, and roads\textsuperscript{23} (Figure 1). We found that 23\% of the Amazonian terrestrial lowlands, 24\% of the rivers, 25\% of the wetlands, and 28\% of the Amazonian Andes are under at least one category of impact activity (Figure 2). The most impacted areas are located south of the Amazon River, in the Brazilian Shield\textsuperscript{24}, and in the eastern Amazon\textsuperscript{24} (Figure 1). Fires, followed by mining and deforestation, impact the largest extents of the Amazon (Figure 2). One or more of these activities are found within several Protected Areas and Indigenous Territories (Figure 3).

**Threats to ecosystem connectivity in the Amazon**

The Amazon rainforest is known for its high heterogeneity, both in terms of its biodiversity and ecological structure. This heterogeneity is a key factor contributing connectivity between ecosystem exchanges allowing the resilience of the Amazon ecosystems. Landscape connectivity between the Andes and lowland Amazonia creates and maintains environments for a vast number of species\textsuperscript{12,13,25}. By regulating geomorphological processes such as river meandering, sediment deposition, and floodplain formation, unimpeded river flows also ensure healthy ecosystem function\textsuperscript{26}. However anthropogenic activities are threatening these processes, affecting Amazonian ecosystems up to hundreds to thousands of times faster than natural processes\textsuperscript{27}. 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. The impacts of dams extend to the whole river basin, altering downstream flood regimes and impacting areas over hundreds of kilometers away from the reservoir\textsuperscript{28,29}. Dams cause ecosystem loss and severe changes in the hydrological regimes of flooded forests, impacting ecosystem dynamics\textsuperscript{29,30} and species composition\textsuperscript{31,32}. Dams also hinder climate change mitigation, given that underwater biomass decomposition leads to the emission of both carbon dioxide and methane\textsuperscript{9}.

Our dataset includes 253 dams in operation in the Amazon by 2020 (Amazon and Araguaia-Tocantins basins), 97 dams under construction, and 483 more in planning stages\textsuperscript{16} (Figure 4). This number can be underestimated since Caldas et al.\textsuperscript{33} 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 (Figures 4). 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\textsuperscript{33}.

Although dam reservoirs cover just 4\% of Amazonian Andes (Figure 2), they impact a disproportionately larger region due to the interruption of sediment, nutrient, and species flows. Dams in the Amazon basin have already caused changes in the community structure and functional traits of fish, leading to the decline in fisheries both upstream and downstream of the dams, altering other communities of animals, and producing both environmental and social impacts\textsuperscript{34,35}, including displacement and loss of
land, loss of livelihoods and cultures, territorial conflicts and tensions, diseases, loss of food provision, and so much more\textsuperscript{36,37}. In general, the existing network of Protected Areas in the Amazon basin is poorly designed to preserve the biotic connectedness of aquatic ecosystems\textsuperscript{38}.

To maintain what remains of Andes-Amazon connectivity, it is key to avoid building new large-capacity (≥10 MW) dams in Amazonian rivers\textsuperscript{9}. Even the construction of dams with installed capacity <10 MW should be evaluated carefully because of their cumulative effect of blocking multiple tributaries\textsuperscript{9}. In cases of dams with installed capacity <10 MW, which would power a single town or village, must consider the rivers’ flows, and may follow the proper environmental licensing and use a risk-based approach\textsuperscript{9,39–41}. We further recommend maintaining the few rivers (and riverine vegetation) that currently lack dams —mainly the Japura, Putumayo, 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 a sanctuary for the Andes-Amazon aquatic connectivity (Figure 4). Succeeding in the establishment of these proposed sanctuaries requires a strong political commitment and agreements involving the governments of Brazil, Ecuador, Colombia, and Peru. Others 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\textsuperscript{33}; efforts should also be directed to 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 cover into pasture and croplands\textsuperscript{9,42–44}. 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\textsuperscript{31,45}, and threatening human safety and well-being, especially of IPLCs\textsuperscript{46}.

Until 2020, 7% of Amazonian wetlands, 9% of the Amazonian Andes, and 10% of lowland forests were deforested (Figure 2). 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\textsuperscript{47,48}. The region’s most severely impacted by deforestation are on the southeastern edge and in the eastern portion of Amazonia in Brazil and Bolivia (Figure 1). These areas have a history of governmental incentives for unsustainable rural development, fueled by forest exploitation and land use change\textsuperscript{49,50}. Practices such as the slash-and-burn are directly associated to aggressive deforestation\textsuperscript{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. IPLCs are known to effectively protect biodiversity\textsuperscript{52} and most of the areas occupied by Indigenous peoples in the Amazon are forested\textsuperscript{53}.

Therefore, the formal recognition of Indigenous Territories and the establishment of new Protected Areas are, again, at the core of biodiversity conservation and ecosystem connectivity. These efforts should provide technical and financial support to guarantee the conditions for the implementation of IPLC’s territorial management,
protection strategies, and restoration incentives. As such, we join the United Nations in the decade of restoration (https://www.unwater.org/news/united-nations-general-assembly-declare-2021-2030-un-decade-ecosystem-restoration) and support the creation of Arcs of Restoration as suggested by Barlow et al.54 across the southern and southeastern Amazon in Brazil and Bolivia and in the Andean foothills of Colombia, Ecuador, and Peru, to recover lost forests and halt the advance of the deforestation frontier.

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 annually55. Fire is not part of Amazonian rainforest natural dynamics and is mostly associated with anthropogenic activities56. 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 use57–61. 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 forests54 and Amazonian wetlands (Figure 1). The increased frequency, duration, and intensity of droughts also increase the likelihood of fires in the Amazon and vice-versa, in devastating feedback loop55,56,62. Again, a combined effort (government, NGOs, local communities, and the scientific community) is needed to prevent and control forest fires61.

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 world63. Most mining is conducted by large international corporations42, and it is largely export-oriented. 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 use64,65, 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 ore66) and humans. Furthermore, the lack of monitoring has already resulted in catastrophic environmental situations in South America, severely degrading human health and welfare67–69.

Illegal mining is even more complex because of the lack of any environmental regulation and the violation of Protected Areas and/or Indigenous Territories, risking the lives of local people both from direct violence and due to widespread and uncontrolled use of mercury69–71, which has strongly impacted aquatic and semi-aquatic biota66. 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 areas72, which fortunately was revoked by the new government73. Economic pressures, however, continuously influence legislation; during May 2023, Brazil's lower house of Congress approved regulations that limit the recognition of new indigenous lands, 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 1980s17.

Large areas of eastern Amazon are currently being explored for mineral resources (Figure 1), including Protected Areas and Indigenous Territories (Figure 3). Both legal and illegal mining
exploitation has recently advanced to new frontiers in northern and central Amazon, with 45,065 mining-prospection concessions or concessions waiting for approval, 21,536 of which overlap with Protected Areas. Restoration of areas impacted by mining should be funded by mining companies, but executed by independent research centers or universities. Stopping illegal mining is a much more complex but urgent endeavor, requiring community engagement and the direct and committed involvement of governments.

**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 construction, land cover changes, ecosystem fragmentation, and surface and underground water contamination. Oil spills pose an additional risk, having occurred numerous times in Colombia, Ecuador, and Peru. Although the impacts of oil spills on aquatic biodiversity and human health are massive, the damages usually remain unrepaid, as exemplified in the Texaco/Chevron case in Ecuador.

Many areas (>36,000 km²) under oil and gas exploitation/exploitation are in Protected Areas or Indigenous Territories (Figure 2); more than 16,000 km² have been solicited by companies and more than 72,000 km² recognized as potential areas for future exploration/exploitation. We recommend prohibiting oil and gas exploitation in Protected Areas. Indigenous Peoples should be consulted for any new project within their lands. 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.

**Roads:** Roads constitute one of the main causes of deforestation in the Amazon. Highways spawn networks of roads, known as the fishbone deforestation pattern, leading to uncontrolled human migration, invasions, and new settlements. 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.

Roads facilitate ecosystem degradation, a pattern that is also evident in the Amazon basin (Figure 1). We recommend avoiding road construction in areas where ecosystems are still minimally impacted, and within Protected Areas and Indigenous Territories. 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 that the percentages of ecosystem disruption are lower in Indigenous Territories (3%) and Protected Areas (5%) relative to other areas (17%). Recognition of their importance, demarcation of Indigenous Territories, and creation of new Protected Areas in regions of illegal occupation are essential. For instance, there are 560,000 km² of non-private lands (“terras devolutas”) in the Brazilian Amazon. The current federal government is proposing to title Indigenous Territories and create new Protected Areas in most of these large areas. We highlight, again, that Protected Areas with local communities and Indigenous Territories are crucial to maintaining the Andes-Amazon connectivity and they should be recognized as the central strategy to have an Amazonia connected and functionally healthy (Figure 3).
When comparing connectivity within Indigenous Territories, Protected Areas, and non-protected areas in the different environments, the Indigenous Territories have significantly higher connectivity, followed by Protected Areas and areas with no protection (Table 1). Although we acknowledge that governance of Protected Areas is complex, it is also clear that they have a positive impact on conservation; deforestation rates within Protected Areas were 1.6 to ten times lower than those in non-Protected Areas\textsuperscript{97-99}, while Indigenous land lost forests between 4.85 (year 1985) and 13 times (year 2000) less than adjacent non-Indigenous Territories\textsuperscript{100,91}. Protected Areas account for 21% of Amazonian Andes, 26% of Amazonian lowlands, 28% of wetlands, and 19% of rivers, while Indigenous Territories account for 26% of Amazonian Andes, 31% of Amazonian lowlands, 23% of wetlands, and 21% of rivers (Figure 2).

Much of Indigenous Territories and Protected Areas are under pressure from agribusiness and illegal activities. Additionally, changes in laws and policies have greatly increase threats to these areas\textsuperscript{92}. For instance, in Brazil, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAM)\textsuperscript{93,94}, which was implemented in 2004, reduced deforestation, but was interrupted in 2019. Furthermore, new laws in Brazil allowed more economic activities within Indigenous Territories and reduced the governance within Protected Areas\textsuperscript{95}. 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.

The recognition of Indigenous Territories and areas of traditional communities, forestalling their bioeconomy, while increasing their quality of life, is crucial for Amazonia conservation. The idea that forests without humans are viable strategy for conservation has been proved erroneous in the Amazonian context. Forest loss is substantially curbed by Indigenous Territories\textsuperscript{99-94}, and the control of illegal activities is much more effective with IPLCs occupation.

Our analysis also demonstrates that economic activities also threaten currently recognized Protected Areas and Indigenous Territories, mainly in the southern Amazon basin (Figure 3). We quantified more than 27,000 km\textsuperscript{2} with at least one impacting activity in Protected Areas and 178,000 km\textsuperscript{2} in Indigenous Territories (Figure 2). Existing Protected Areas and Indigenous Territories, in conjunction, form a promising scheme for ensuring connectivity, but appropriate funding and management plans 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 \textit{Arapaima gigas} along the Juruá and Upper Amazon rivers\textsuperscript{96,97}). Securing and expanding collaborative partnerships to maintain and recover fisheries and floodplain ecosystems should be a priority\textsuperscript{98}. Guaranteeing effective governance with the IPLCs’ protagonist, inhibiting illegal activities, and respecting their lifestyle promoting a standing forest and flowing rivers bioeconomy is the fastest, most effective, and cost-effective strategy to conserve Amazonia.

A robust follow-up mechanism involves continuous monitoring of connectivity indicators, regular policy evaluations, and adaptive management strategies. Engaging local communities, scientists, policymakers, and international organizations will be crucial for the success of these policies. Regular reviews and adjustments will ensure that conservation efforts remain effective in the face of evolving challenges.

**Conclusions**

Based on an analysis of the major current impacts on the Amazon basin (dams, deforestation, fires,
mining, oil and gas exploitation, and roads), we conclude that the integrity of Indigenous Territories and Protected Areas is the most important and viable way to maintain aquatic and terrestrial habitat connectivity in the Amazon basin.

Parallely, we identify sanctuaries that need protection to maintain landscape 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 Churumbeles, 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 Amaraquei. 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 (Figure 4). These restoration efforts should have the goal of recovering ecosystem function, connectivity, and biodiversity in impacted areas, a challenge especially suited to put into practice during the United Nations Restoration Decade. Restauration should go, hand-to-hand, with socially just and sustainable economic activities\textsuperscript{14}.

Since anthropogenic activities are heterogeneously distributed in Amazonian ecosystems and 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 allows local communities to maintain their livelihoods within largely intact ecosystems\textsuperscript{97}. Also, Indigenous Peoples play a significant and unmeasurable role in controlling deforestation, maintaining biodiversity, reducing forest carbon emissions, and consequently mitigating climate change\textsuperscript{95,99}. Our study clearly shows that current Indigenous Territories and Protected Areas connect the main ecosystems in the Amazon basin. If they are respected and supported, biodiversity and connectivity will be ensured.

Material and Methods

To identify landscape connectivity considering anthropogenic impacts as resistance to ecosystem function, we mapped ecosystem connectivity in three focal Amazonian environments: terrestrial lowlands, seasonally flooded lowland wetlands, and rivers (Figure 1). To delimit the study area, we used the wetlands map produced by the Large-Scale Biosphere-Atmosphere Experiment\textsuperscript{100}. We defined terrestrial lowlands as non-flooded areas <600 m of elevation\textsuperscript{24}, and Tropical Andes as ecosystems at ≥600 m elevation within the Amazon basin. Terrestrial lowlands were bounded by non-flooded humid and dry forests and seasonally dry and burned savannas. Wetlands were defined as seasonally flooded forests, swamps, and estuaries.
Large rivers (Strahler stream orders 6-10⁶) were identified from HydroRivers\textsuperscript{101}.

We compiled data for the six major anthropogenic activities that affect connectivity of Amazonian ecosystems: dams\textsuperscript{16}, deforestation\textsuperscript{16}, fires\textsuperscript{16}, mining\textsuperscript{16}, oil and gas exploitation\textsuperscript{16}, and roads\textsuperscript{23}, using a pixel size of 180 m on a side. We mapped and calculated the proportion of areas impacted by each activity (number of pixels under the activity divided by total number of pixels) for each of four focal environments (Tropical Andes, Lowland non-floodplain forests, wetlands, and rivers; Figure 1). We then stacked the maps of each activity and summed the pixels to calculate the degree of impact at each pixel, with no anthropogenic activity having a value of zero and each activity having a value of 1, such that pixels ranged in values from zero (no anthropogenic activity) to six (all activities present).

To assess ecosystem connectivity, we generated a resistance layer. Resistance can be considered the basis of connectivity analyses, which indicates the degree that a landscape difficult or facilitate the biotic and abiotic movements across a given landscape being influenced by the degree of ecosystem degradation combined with the existence of natural or anthropic barriers (e.g., large rivers in terrestrial landscapes or large dams in a river). We generated the resistance layer based on the impact value\textsuperscript{101} of each human activity, with adjustments depending on the focal environment (e.g., dams are major barriers for river connectivity, but not for terrestrial connectivity; Table S1). As terrestrial areas are not suitable for rivers flow, we considered it as infinite values (NA in the analysis), but as wetlands are seasonally flooded environments it was considered a high resistance for terrestrial environments and low resistance for rivers (Table S1).

The resistance raster obtained for each focal environment was used to extract functionally connected areas (polygons) within which organisms or ecosystem functions may move freely below a threshold value. Because landscape heterogeneity varies with scale, we used the ‘grainscape’ package v.0.4.4\textsuperscript{102} in R v.4.2.2\textsuperscript{103} to extract lattice-based connectivity units following Galperna et al.\textsuperscript{102} Lattice-based analyses find the connectivity relationships for a lattice of focal points superimposed on the raster resistance surface, and do not need to identify focal patches a priori to generate the connectivity network. For the terrestrial landscape, the lattice was a grid of 25 km uniformly spaced focal points, and the functionally connected regions (grains of connectivity) were extracted for thresholds from 25 to 500 at 25 units steps. Under this protocol, the use of smaller values results in maps that consider, as functionally connected, only pixels that are geographically close to each other, generating small polygons, especially if the resistance values are high. Larger values of threshold, in contrast, produce a coarser spatial grain, with larger polygons. The optimal threshold was set to 275, and the centroids of the generated network of connected regions were used to generate a kernel density map of non-connected regions (Figure 2). High centroid density means a high resistance (low connectivity) and vice versa. For rivers and wetlands, we selected 20,000 random pixels of each target environment as focal points. The threshold was set to zero to present the more stringent and conservative possible results.

To evaluate the importance of ITPAs on the ecosystem connectivity in the terrestrial environment, we transformed the kernel resistance density values in connectivity by multiplying by -1 and summed with the lowest value in each of the three different focal environments. To evaluate the importance of ITPAs on rivers and wetlands, we counted the number of polygons inside non-protected areas, PAs and ITs, accounting for differences in area. As these data are strongly heteroskedastic (Bartlett’s test p < 0.001 for all landscapes), and because we seek to test directionality (greater or lesser than, not just differences), we ran an one-way ANOVA for
heteroskedastic data using the function 'oneway.test' in R, followed by a post-hoc test using the 'pairwise.t.test' function with 'pool.sd = F' to account for the inequality of the variance using the Welch approximation. Additional R packages used for data curation were tidyverse v.1.3.1\textsuperscript{104}. Maps were produced using QGis software\textsuperscript{105}.

References

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Figure 1. Six major anthropogenic activities in the Amazonian Andes (dark gray), Amazonian lowland wetlands (purple), Amazonian rivers (blue), and Amazonian lowland terrestrial ecosystems, including rainforests and savannas (light gray).  
A) South America showing the Amazon Basin limits analyzed here. B-G) Impact of each anthropic activity as of 2020 shown in red.  
B) Dams in operation and under construction;  
C) Deforestation; note the high disturbance in the Tropical Andes and the Southeastern basin (Brazil and Bolivia);  
D) Fires;  
E) Legal mining under exploration and/or exploitation; also shown are areas with concession for mining (orange) and illegal mining (dark red);  
F) Oil and Gas exploration and/or exploitation; and  
G) Roads.  
H) Combined impact activities. Color shading represents numbers of anthropogenic activities, ranging from yellow (one activity; 24% of Amazonian Andes, 23% of wetlands, 36% of rivers, and 17% of lowland rainforests), orange (two activities; 4% of Amazonian Andes, 2% of wetlands, 3% of rivers, and 5% of lowland rainforests), light red (three activities; less than 1% in all areas), red (four activities; less than 1% in all areas) to dark red (five activities; less than 1% in all areas). For better visualization we add dams, rivers, and roads as shape files up to the rasters.
**Figure 2.** Human impacts in the Amazon basin. **A)** Proportion of area impacted by each of six anthropic activities in the Amazonian Andes (dark gray), lowland forests (light gray), wetlands (purple), and rivers (blue). **B)** Proportion of area within Indigenous territories (light brown), Protected areas (green), and no protected areas (magenta) in the Amazonian Andes, lowland forests, wetlands, and rivers. **C)** Proportion of area impacted by each of six activities in Indigenous territories (brown), Protected areas (green), and no
protected areas (magenta). **D)** Proportion of area not impacted by any anthropic activity (green), by one activity (yellow), two activities (orange), and three activity (red) in the Indigenous territories, Protected areas, and no protected areas.
Figure 3. Ecosystem connectivity in the Amazon basin. A) Amazonian forests (including white-sand ecosystems, and savannas), with kernel density connectivity map (see text), with Indigenous Territories (ITs) and Protected Areas (PAas) are showed as polygons with regular and random points, respectively. Circled areas represent priorities for terrestrial connectivity in the Andes/Amazon interphase. B) Wetlands (i.e., swamps and seasonally flooded savannas) showing large regions of functionally connected area at threshold = 0, the cluster 1: Amazon River (~553,000 km²), cluster 2: Beni flooded savannas (~141,000 km²), cluster 3: upper Xingú River (~26,000 km²), and non-connected wetlands. C) Large rivers (stream orders 6-10) showing large regions of functionally connected area at threshold = 0 with the resistance layer overlapped, in this focal environment mostly dams and illegal mining. Note that Indigenous territories and other Protected areas are crucial to maintaining ecosystem connectivity.
Figure 4. Anthropogenic impacts in the Amazonian Andes and Western Amazonia. A) Accumulated anthropogenic activities (ranging from 1 to 5, from yellow to dark red). Colored regions: Indigenous Territories (dotted dark green areas), Protected Areas (dotted light green areas) including dams; large (red dots), small (orange dots), under construction (dark red crosses), and planned (yellow triangles). B) Rivers considered crucial for maintaining Andean-Amazon connectivity (in white): Japurá, Putumayo, Beni, and Madre de Dios are unique because no dams interrupt their flow. We propose that these rivers (and their riverine ecosystems) should be considered connectivity sanctuaries.
Table 1. Mean and standard deviation of Kernel density (terrestrial landscape) and number of disruptions (for wetlands and rivers landscapes) for the Indigenous Territories, Protected Areas, and non-protected areas. Pairwise test from ANOVA results for terrestrial ($F = 4963085, p < 0.001$), wetlands ($F = 92.128, p < 0.001$), and rivers ($F = 58.088, p < 0.001$) with all group differences significant ($p < 0.001$).

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<th>Terrestrial</th>
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<th>Rivers</th>
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<td>$2 \pm 0.48$</td>
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**Table S1.** Impact values for each human impact and focal environment.

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<tr>
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