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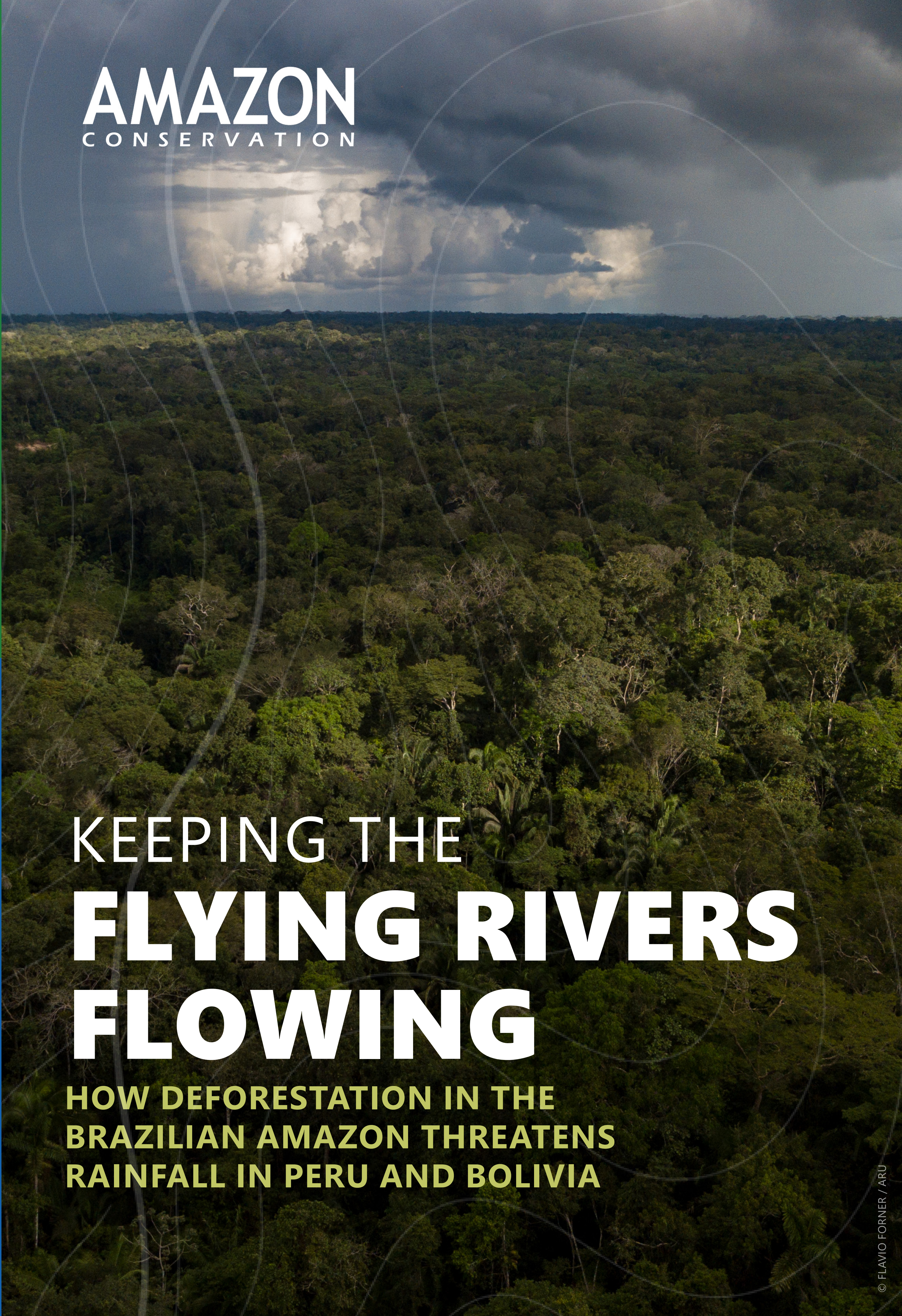

KEEPING THE
FLYING RIVERS FLOWING

HOW DEFORESTATION IN THE BRAZILIAN AMAZON THREATENS RAINFALL IN PERU AND BOLIVIA

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The authors are grateful to Wei Weng, Julia Péret, John Beavers, Andrés Santana and Helena Ceneviva for their careful review of earlier drafts and their many constructive suggestions.

This work was made possible thanks to the generous support of the Leo Model Foundation, Jeff and Connie Woodman, the Aristotelian Foundation, and other generous supporters of Amazon Conservation Association.

Publication Credits and Acknowledgments

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How to cite:
Amazon Conservation. (2026). Keeping the Rivers Flowing - How Deforestation in the Brazilian Amazon Threatens Rainfall in Peru and Bolivia.

Amazon Conservation. Available at www.amazonconservation.org/publication

Foreword by Carlos Nobre

The Amazon - the largest tropical forest on Earth - is a living system that regulates global climate and sustains unparalleled levels of biodiversity. It also generates atmospheric moisture flows across South America, which we have come to understand as flying rivers. These invisible rivers carry water across the continent, sustaining rainfall patterns that support forests, agriculture, and societies far beyond the Amazon itself.

Over the past decades, scientific evidence has made clear that this system is approaching a critical threshold. Together with my dear colleague Tom Lovejoy, who sadly passed away at the end of 2021, I have warned that continued deforestation and climate change could push the Amazon toward a tipping point, where large portions of the forest may no longer be able to sustain themselves. The weakening of flying rivers is central to this risk. As forest cover is lost, the capacity of the rainforest to recycle moisture declines, increasing the likelihood of drought and accelerating systemic collapse.

This white paper by Amazon Conservation represents an important and timely contribution to this body of knowledge. By identifying the forests most critical to maintaining atmospheric moisture transport, it offers a practical pathway from science to action. It helps us move beyond general calls for conservation toward a more strategic approach that prioritizes areas essential for sustaining rainfall and reducing climate risk across the region.

For governments, funders, and the broader conservation community, the prioritization framework presented here can help align policy, finance, and conservation efforts with the realities of this interconnected system. These findings and recommendations are particularly relevant to the Amazon Cooperation Treaty Organization (ACTO)'s Strategic Cooperation Agenda. Responsibility for the conservation of the Amazon has long been debated in global fora. It is time for the regional dimensions of its management to be understood and acted upon with the same urgency.

The window to act is still open, but it is narrowing. Strengthening the resilience of flying rivers through science-backed, prioritized conservation actions is a vital step in the right direction. This white paper offers a valuable, actionable guide to doing so.

Carlos A. Nobre

Executive Summary

Flying rivers are atmospheric moisture flows that travel from the tropical Atlantic across the Amazon Basin to the foothills of the Andes, sustained by the evapotranspiration of Amazonian forests. Forests (tree and woody vegetation) and non-forest ecosystems (savanna, grasslands, others) of the southwestern Amazon — particularly in Peru and Bolivia — depend on this process for more than 70% of their annual precipitation. Deforestation along these pathways disrupts moisture recycling, reducing rainfall over areas whose communities have no influence over the land-use decisions that determine their water supply.

This white paper charts the seasonal pathways of flying rivers to the sensitive areas of Peru and Bolivia, maps the deforestation risks they face, assesses the exposure of southwestern Amazon economies and ecosystems to a breakdown of this system, and issues six recommendations to policymakers in Peru, Bolivia, and the international community, mainly in Brazil.

I. Seasonal pathways and deforestation risks

Moisture transport to the southwestern Amazon follows three distinct seasonal pathways. Using ERA5 reanalysis data and backward streamline integration, this paper maps each pathway and overlays it on deforestation risk data, land designations, and planned infrastructure to identify where continuity of moisture transport is most at risk.

The **dry season pathway** is the most exposed: it already flows over heavily deforested land in southern Pará, is interrupted by multiple undesignated public forest gaps, and is crossed directly by federal highway BR-319, whose imminent paving could trigger up to 5 million hectares of additional deforestation. This is also the season when moisture recycling from vegetation is most critical, making this the highest-risk corridor. The **transition season pathway** crosses vast expanses of undesignated public forests in the western Amazon that, while not under immediate pressure, lack the legal protection needed to prevent eventual conversion. The **wet season pathway** flows over areas with relatively strong existing protection and faces more limited near-term risk. However, before reaching Peru and Bolivia, all three pathways converge over the state of Acre, where several planned road projects — including a proposed international connection to Pucallpa in Peru — could disrupt year-round moisture transport.

II. Exposure of the southwestern Amazon to drought

The 2023–2024 Amazon drought — the most severe on record — illustrates what a sustained reduction in flying river functionality could mean. Its causes were multiple, but it shows the scale of exposure across four sectors:

- **Agriculture**: soy production in Santa Cruz, Bolivia fell 75%; potato harvests in Puno, Peru dropped from 998,000 to 596,000 tons in a single year; rice farming in the Beni and smallholder agriculture across Madre de Dios were severely disrupted. Heavy reliance on rain-fed farming with limited irrigation access makes the region acutely vulnerable to precipitation variability.

- **Forests and rural livelihoods**: Brazil nut production — the economic backbone of forest communities across Madre de Dios and Pando, directly supporting around 27,000 people in Peru alone — is highly sensitive to drought. Where forest-based livelihoods remain viable, deforestation pressure tends to decrease; where they collapse, pressure for deforestation tends to increase.
- **Ecosystems and Species**: the Tropical Andes are among the most biodiverse regions on Earth, with 25–50% of many taxonomic groups found nowhere else. Even small reductions in moisture availability can trigger large ecological responses: widespread tree mortality, altered fire regimes, and carbon release from high Andean wetlands that function as significant carbon sinks.
- **Reciprocal river systems**: flying rivers also feed river systems that flow eastward back into Brazil. Around 60% of the Madeira River's discharge originates from Bolivian and Peruvian tributaries. During the 2023–2024 drought the Madeira fell to a 122-year low, halting navigation at Porto Velho, cutting hydroelectric output, and isolating communities. The consequences of Brazilian deforestation therefore extend back into Brazil itself.

III. Recommendations

The paper issues six recommendations to governments, conservation funders, and regional institutions:

- **Require environmental and strategic impact assessments for road projects to account for transboundary atmospheric moisture transport**. The BR-319 and BR-364 processes are live. Any road development should include transboundary impact assessments covering socio-ecological effects on Peru and Bolivia, designation of protected areas along corridors, and strict measures against side-road construction — especially urgent given the proposed regulatory flexibilization of environmental licensing in Brazil.
- **Add atmospheric moisture transport as an explicit criterion for protected area designation and conservation funding**. Existing conservation planning frameworks do not capture transboundary hydrological services. A sixth criterion based on contribution to flying river functionality — operationalized through "Critical Moisture Territories" — should guide the designation of approximately 50 million hectares of Undesignated Public Forests (UPFs), where 26–30% of Amazon deforestation currently occurs. Financing vehicles including ARPA, the Amazon Fund, and the Tropical Forests Forever Fund should integrate this criterion into their allocation decisions.
- **Accelerate large-scale forest restoration in the eastern Brazilian Amazon, targeting the degraded dry and transition season corridors**. Southern Pará is a priority. Existing programs such as Restaura Amazônia and Brazil's PLANAVEG target of 12 million hectares by 2030 are an important start, but investments must be substantially scaled up, targeted to key hydrological corridors, and integrated with climate and land-use policies.
- **Develop regional governance frameworks that recognize Brazil's asymmetric responsibility for the atmospheric moisture system**. Brazil controls approximately 60% of the Amazon Basin and near-total control over the flying rivers that supply moisture to Peru and Bolivia. The Belém Declaration was a step forward, but set no quantitative targets by country and established no differentiated responsibilities. Progress requires binding bilateral or multilateral agreements — modeled on transboundary water management

frameworks — establishing Brazil's obligations to maintain forest cover in areas critical for moisture transport.

- **Develop ecosystem-based climate adaptation strategies in the sensitive areas of the southwestern Amazon**. Forest-based adaptation measures piloted in Pando, Bolivia should be extended to Northern Beni, Santa Cruz, La Paz, and equivalent Peruvian departments, developed in coordination across Brazil, Peru, and Bolivia, and explicitly designed to account for the risk of reduced atmospheric moisture transport alongside other climate stressors.
- **Invest in a targeted technological innovation and research agenda to strengthen the evidence base for policy**. Priority areas include: modeling how restoration in the southeastern Amazon would improve dry season moisture transport; refining the mapping of moisture corridors with cumulative deforestation impacts; projecting how climate change will shift the seasonal pathways; expanding monitoring networks linking precipitation and river flow across the Amazon–Andes system; and strengthening research capacity in Amazonian countries for early warning and adaptation planning.


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Introduction

The natural phenomenon of aerial moisture transport and recycling, popularized in the press as "flying rivers" (also known as "aerial rivers"), has emerged as an essential concept related to the conservation of the Amazon. Flying rivers are the long-term and large-scale preferential pathways of atmospheric moisture flow across the Amazon[1]. In this process, moisture evaporated over the tropical Atlantic is transported westwards, over the Amazon, all the way to the Andes. These rivers follow different pathways across the Amazon basin, based on the time of the year ("seasonal pathways").

This transport over large distances is made possible by a combination of trade winds flowing consistently east to west and the "recycling" of moisture, whereby precipitation over Amazon soils, water bodies and forests, evaporates back into the atmosphere including the vegetation's foliage, allowing it to be transported further downwind.

Forests and ecosystems of the southwestern Amazon in Peru and Bolivia (henceforth designated as "sensitive areas") are particularly dependent on these "flying rivers" that originate thousands of kilometers away over the Atlantic Ocean and travel across the Brazilian Amazon. These sensitive areas are also characterized by extremely high levels of biodiversity, and communities with limited access to potable water systems, making them even more susceptible to the impacts of water stress. Yet, these flying rivers that sustain Peru and Bolivia's forests, agricultural systems, and water resources are increasingly threatened by expanding deforestation fronts. **Should tree cover be removed along their path across the Brazilian Amazon, moisture transport could be significantly reduced**, or changes in atmospheric circulation could redirect moisture toward other regions, **thereby affecting rainfall over the sensitive areas**. Beyond local effects, such a change could bring about impacts across the entire region, pushing the Amazon closer to its 'tipping point'.

The scientific understanding of the importance of flying rivers as a hydrological service is growing. However, much of the available literature on the flying rivers in the Amazon highlights their crucial role in the precipitation regime of the vast agricultural areas of central-western Brazil and the Rio de la Plata Basin[2]. Cross-border dependencies have been explored, albeit in general terms[3].

The aim of this white paper is to define forest conservation and restoration priorities based on the path of flying rivers over areas at risk of deforestation. To do this, we:

I. Chart the path of flying rivers to sensitive areas in Peru and Bolivia that depend on them, and identify locations along their path that are most threatened by deforestation,
II. Assess the vulnerabilities of these sensitive areas, including the Andes-Amazon transition zone, a major global biodiversity hotspot and important center of agricultural and forest production for Peru and Bolivia, to a breakdown of flying river functionality,
III. Issue recommendations to reduce the risk of disruption to flying rivers and build the governance, conservation, and adaptation frameworks needed to protect dependent communities and ecosystems."

I. Flying river pathways and deforestation risks

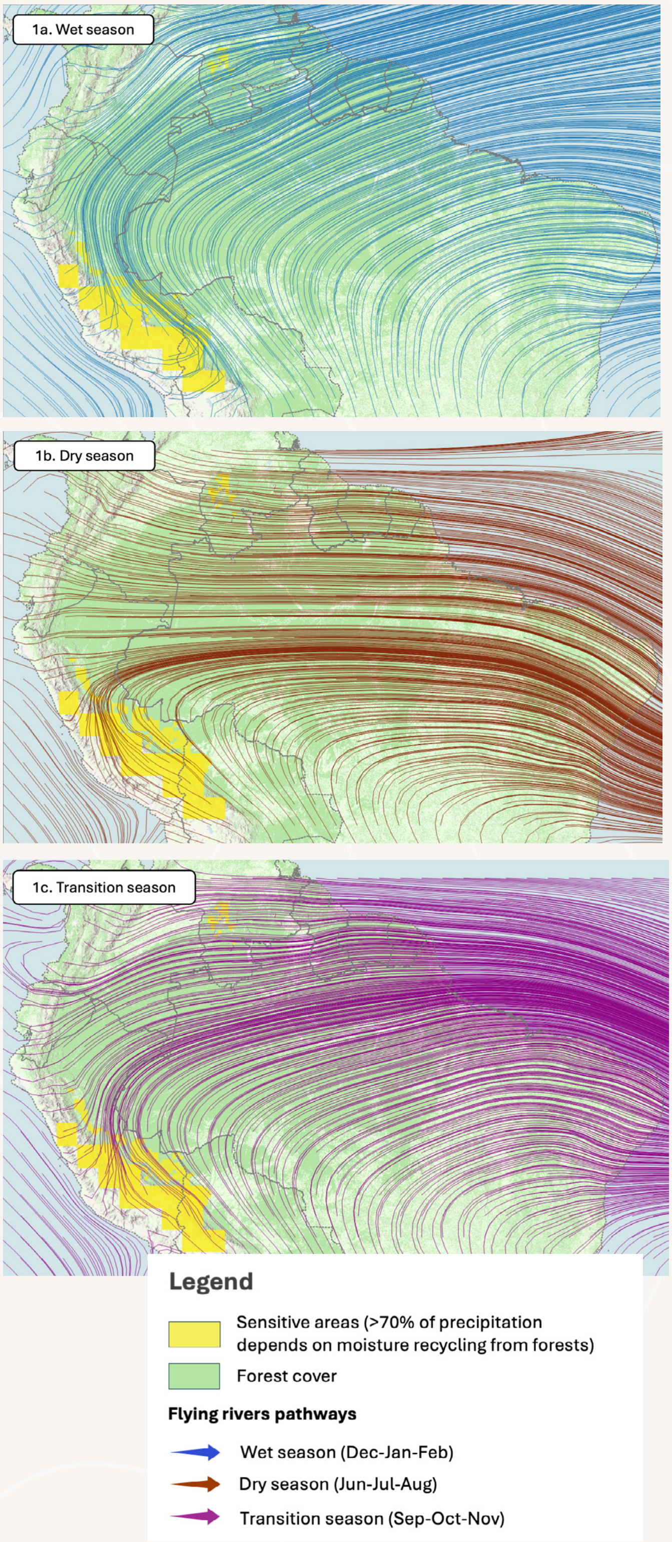
How flying rivers work

Atmospheric moisture transport from the Atlantic to the Andes, aided by moisture recycling from vegetation, takes place across the entire Amazon. However, some regions are more dependent on it than others. The most vulnerable areas lie in the Andes-Amazon transition zone, including the southwest Amazon lowlands — spanning only two of the nine Amazon Basin countries: Peru and Bolivia (see Annex I for more details). Moisture transport to these sensitive areas follows seasonal patterns across three main periods. The seasonal pathway of these "flying rivers" shifts significantly across these three periods, as documented in MAAP Report 232.

During the **wet season (December-January-February)**, nearly 50% of total annual precipitation falls over the region, recharging Amazonian groundwater reserves vital for sustaining forest transpiration and river flow during the dry season[4]. During that period, moisture flows to the sensitive areas originate off the Guianas coast and travel southwestward, arching along Brazil's borders with Venezuela, Colombia, and Peru (Figure 1).

During the **dry season (June-July-August)**, evapotranspiration-driven moisture recycling is particularly important to ensure that limited

Figure 1. Pattern of moisture transport from the Atlantic to the Andes across the year



precipitation reaches the western Amazon[5]. Moisture flow to the sensitive areas enters from the tropical Atlantic off northeastern Brazil, crosses the basin along a much more narrow and concentrated pathway that curves slightly northward, then turns abruptly south upon meeting the Andes (Figure 1b).

During the **transition season (September-October-November)**, tree-transpired moisture plays an important role in triggering the onset of the rainy season[6]. The moisture flow then originates along the northernmost coastal areas of Brazil near the Guyanas and travels westward to the Peru-Brazil-Colombia border before curving South to the sensitive areas (Figure 1c).

As can also be seen seen in Figure 2 (below on page 13), when streamlines reach the sensitive areas, increased arrowhead density signals reduced flow speed and enhanced moisture convergence — conditions that favor precipitation and the deposition of moisture originally evaporated over the Atlantic and recycled across the region through evapotranspiration. Conversely, long arrows indicate high wind speeds carrying humidity across large distances.

For more details on data and methodology used for this figure, see **Annex I**.

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How deforestation affects flying rivers

Evapotranspiration is widely recognized as a key component of the Amazon's water cycle, and therefore of atmospheric moisture transport from the Atlantic Ocean to the Andes. This is a fast-evolving field of study, and some aspects remain subject to scientific controversy. However, some of the key dynamics at play are already well understood and should inform policymaking:

- Amazonia represents the largest tropical rainforest on Earth. Forests recycle moisture more efficiently and, as a result, are a greater source of precipitation over other terrestrial areas than rangeland or croplands that follow deforestation[7].
- Over 70% of precipitation that falls over the southwestern Amazon comes from moisture that originates in the Atlantic Ocean and has been recycled multiple times by forests across the Basin, making them the most dependent on atmospheric moisture transport within the Amazon region.
- The further away from the Ocean and the closer to the target areas, the more important the role of moisture recycling from vegetation becomes: while moisture recycling covers a vast area from east to west, much of the vegetation-induced rainfall in the southwest Amazon is transpired nearby[8] and areas exerting the greatest direct influence on the southwest Amazon are located just upwind, in the central-west Amazon[9].

Large-scale removal of vegetation along the flying rivers, especially as they get closer to the sensitive areas, is very likely to disturb moisture recycling and transport to these areas.


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Removal of vegetation directly affects evapotranspiration, while massive areas of deforestation can also modify the main atmospheric circulation patterns, changing winds direction and moisture horizontal transport from the Atlantic to the continent, including changes in the date of the wet season onset[10]. Given the magnitude of the potential consequences, a precautionary approach is recommended, and any changes that may disrupt atmospheric moisture transport should be avoided.

This conclusion also highlights the need to assess deforestation risk not only at the scale of the entire Amazon — where, famously, a forest loss threshold of about 20% could cause a tipping point[11]— but also along the pathways of flying rivers, to areas that are highly dependent on them.

Mapping deforestation risks along the seasonal pathways

To understand deforestation risk along the flying river pathways for different seasons, we filtered the moisture transport streamlines from Figure 1 and kept only those leading to the sensitive areas in Peru and Bolivia, across the three seasons. The resulting seasonal pathways were then overlaid on relevant data to understand **where forest cover is more secure**, due to land-use designations as Protected areas and Indigenous territories, **and where deforestation risk is high**, such as projected deforestation risk[12], undesignated public lands[13] and existing and planned road infrastructure[14].

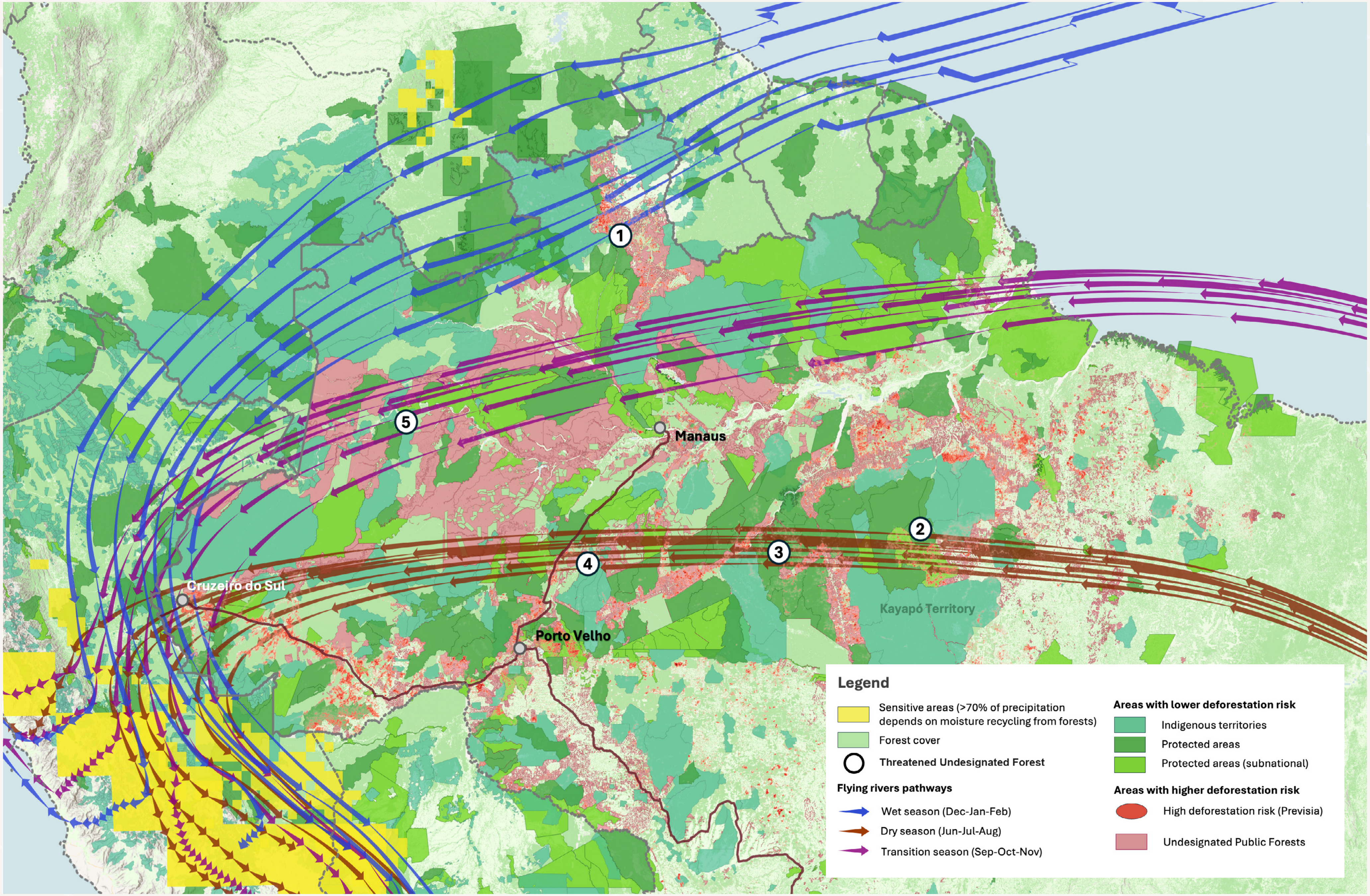
Deforestation in the Amazon is highly concentrated around rivers and roads: one study from 2014 found that 95% of deforestation occurred within 5.5km of a road or 1km of a river[15]. The Previsia dataset builds on this and other input data such as recent deforestation, to forecast deforestation risk, is used here to determine where vegetation cover is at risk of being lost along the flying river seasonal pathways.

The wet season pathway flows over the Guianas, Venezuela, the Colombian Amazon and the department of Loreto in Peru, areas where forests enjoy relatively high levels of protection, due to their designation as either protected areas or officially recognized indigenous territories. Research confirms that all types of protected areas—including strictly protected areas, sustainable use areas, and Indigenous lands—have successfully reduced deforestation[16]. The only potential interruption to this seasonal pathway appears to be in the State of Roraima where high deforestation risk can be seen around the capital Boa Vista, encroaching on several state-level Undesignated Public Forests (**Point 1, Figure 2**).

The dry season pathway enters the continent over Northeastern Brazil and then crosses the Southern part of the State of Pará, where large areas of forest have already been converted to agriculture. There is a high likelihood that this loss of vegetation is already affecting the functionality of the flying river during that season. Some of that functionality may be restored if the natural vegetation is recovered, through either natural regeneration or active restoration. The rest of the pathway appears relatively well covered by protected areas and indigenous territories, although it is interrupted in several places by narrow stretches of Undesignated Public Forests where deforestation risk is high (**Point 2, 3 and 4, Figure 2**).

The dry season pathway is also cut by federal highway BR-319, linking Porto Velho to Manaus. Deforestation in the 13 municipalities along the road is closely monitored, showing persistent encroachment of illegal deforestation on neighboring protected areas and indigenous territories[17]. Conservation organizations have long advocated against the paving of the BR-319, pointing to the failure of measures taken to avoid deforestation along roads built through other parts of the Amazon, despite assurances that the impact would be mitigated. Yet, after decades of advocacy backed by studies of the projected impacts, the approval of Law n. 15.300 in December 2025 opened the way to the advancement of the paving of BR-319 and others in the Amazon region. This law creates the Special Environmental Licensing process, a new process designed to speed the approval process of infrastructure projects

Figure 2. Flying rivers’ seasonal pathways and associated deforestation risk



considered strategic by the government, with the law explicitly including among those projects the "reconstruction and repaving works on existing highways whose segments represent strategic connections". Plans to lay asphalt over the middle section of the road would reopen it to traffic year-round, increasing deforestation risk along its path. Project deforestation risk is high in UPFs Acará and Acarazinho (**Point 1, Figure 3**), directly in the path of both the BR-319 and the dry season pathway. Scenarios of future deforestation along the road forecast vast areas of forest loss reaching up to 50km on each side[18]. Forest cover loss at such a scale, directly interrupting the flying river pathway, would represent a major risk to its functionality.

The transition season pathway flows over the State of Amapá and the Northern half of the State of Amazonas which have historically seen low deforestation rates. As it continues to flow West, it crosses vast areas of undesignated public forests in the western part of the State of Amazonas (**Point 5, Figure 2**). While not under immediate pressure from deforestation, the lack of designation of these vast expanses of forest exposes them to eventual land grabbing and, ultimately, conversion to productive uses and loss of vegetation cover that would significantly reduce their ability to recycle moisture.

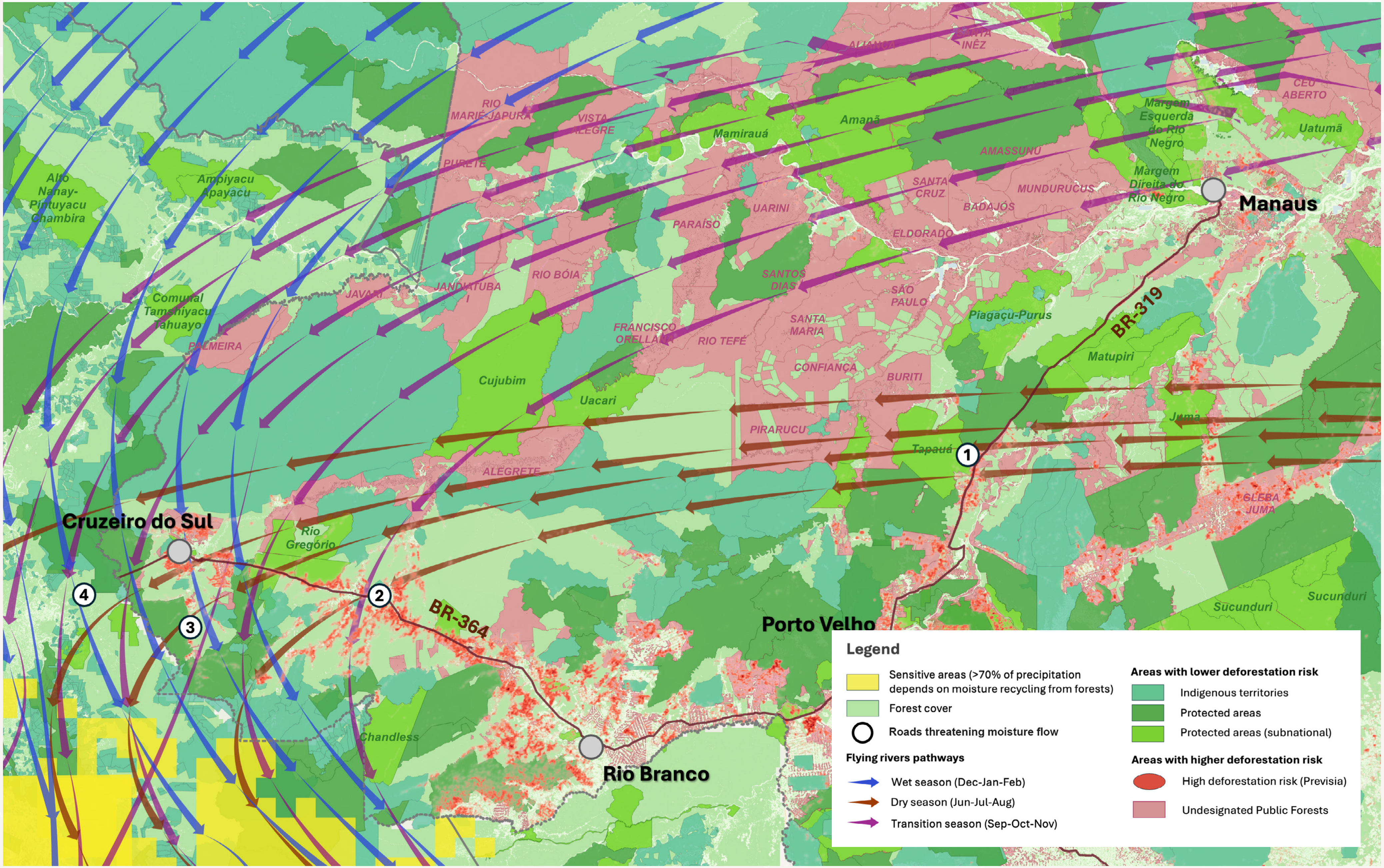
Before reaching the sensitive areas in Southern Peru and Northern Bolivia, **the three pathways converge over the Western half of the state of Acre** and the BR-364 highway, as it reaches the city of Cruzeiro do Sul[19] (Figure 3). Several road development projects are planned in the region, from the repaving of the highway linking Rio Branco, the capital, to Cruzeiro do Sul (Point 2, Figure 3), the opening of new roads connecting Cruzeiro do Sul to smaller cities near the border with Peru which are currently only accessible through river transportation[20] (Point 3, Figure 3) and, most ambitiously, the opening of a new international connection between Cruzeiro do Sul and Pucallpa in Peru[21] (**Point 4, Figure 3**). This connection could represent a new major transport axis that would open a shorter route to the Pacific port of Chancay, a strategic investment to facilitate the export of Brazilian commodities to the Chinese market[22]. Despite strong backing from the State authorities in Acre, the project remains controversial, especially as it would cut through protected areas on both the Brazilian and Peruvian sides[23], and that the economic case remains weak to justify the level of investment required.

While some of these investments in infrastructure improvement may sometimes be justified to facilitate access for remote communities, it is critical that their impact on precipitation in the sensitive areas is accounted for in the execution of strategic environmental assessments. Reduction in vegetation cover in this region could have a particularly high impact on precipitation over the sensitive areas as it intersects all three seasonal pathways of the flying river, meaning that the effect would be felt year-round.

This simple overlay analysis highlights the need for spatially explicit conservation priorities that consider the risk of forest cover loss to flying river continuity — particularly where moisture recycling most directly sustains rainfall in Peru and Bolivia.

In Section III, we present recommendations on how to reduce the risk of disturbance to the flying river pathways. Prior to this, we present a risk assessment of the breakdown of the flying rivers for the sensitive areas in the southwestern Amazon.

Figure 3. Flying river pathways for the three seasons, overlaid on land designations and key road development projects



II. Exposure of the southwestern Amazon to flying river disruption

In risk assessments for climate adaptation and disaster risk reduction, risk is generally defined as combination of hazard (events with the potential to cause harm), exposure (the presence of people or assets that could be affected by the event) and vulnerability (the characteristics and conditions that increase susceptibility to hazards)[24]. The fact that the southwestern Amazon is highly dependent on moisture recycling from Amazonian forests makes it particularly vulnerable to a disruption of flying rivers. Over the Peruvian and Bolivian Altiplano a clear delay in the date of the wet season onset has already been detected, in relation to changes in the large-scale atmospheric circulation patterns, showing that broader climate change is already affecting the region[25]. **The likelihood of continued deforestation in the Brazilian Amazon, combined with climate change that is already affecting precipitation regimes across the globe, represents a significant hazard**. The following section explores the exposure of the economies, livelihoods, and ecosystems of the southwestern Amazon to reduced rainfall across four sectors (agriculture, forests and rural livelihoods, ecosystems and biodiversity and freshwater resources).

The Amazon suffered a severe drought in 2023-2024, which was particularly acute in the southwestern Amazon[26]. Many climatic factors have been proposed to explain this exceptional event, from a particularly strong El Niño to unusual warming of the North Atlantic[27]. This extreme drought started with a major deficit of precipitation over the Peruvian-Bolivian Altiplano, due to a deficit of atmospheric moisture flows from the Amazon to the Altiplano[28]. **While it is not possible to assess the extent to which deforestation in the Brazilian Amazon contributed to this phenomenon, its consequences nevertheless provide** useful evidence **into the exposure of the sensitive areas to drought**, from agriculture and freshwater resource management, forest-based livelihoods, to the conservation status of endemic ecosystems and even the hydrology of downstream river basins.

Agricultural sector

The agricultural regions of Peru and Bolivia, particularly those engaged in crop production for both domestic consumption and export markets, rely on seasonal precipitation patterns that are increasingly at risk of being disrupted by deforestation along the flying river pathways. In 2024, drought caused a staggering 75% drop in soy production in the Santa Cruz region of Bolivia, demonstrating its reliance on rainfed mechanized agriculture[29]. Soybeans, cultivated in the lowlands that are highly dependent on precipitation and runoff, represents 15% of the country's exports[30], meaning that droughts have the potential to affect the country's balance of trade in an already volatile economic situation.

Despite the dominance of cattle ranching, rice production in the Beni lowlands represents a significant and particularly vulnerable agricultural system. The cultivation cycles for rice depend on predictable flooding and recession patterns that are maintained by consistent precipitation in upstream watersheds. Disruption of these patterns due to altered atmospheric moisture transport can result in crop failures, reduced yields, and economic hardship for farming communities. Rice is also a staple that plays an important role in Bolivia's food security, particularly in rural areas where it contributes directly to diet and household consumption. National statistics highlight that rice accounted for nearly 5% of the total cultivated area in 2019, making it one of the principal food crops alongside maize, wheat, and potatoes[31].

However, its yields have shown variability and even a decreasing trend, reflecting both structural and climatic challenges. An agro-food system analysis of Bolivia (2005–2015) found that rice was among the cereals with a downward production tendency, raising concerns over the stability of supply for domestic consumption[32]. This decline in performance contrasts with the rising demand from urban and rural households, reinforcing rice's strategic importance for ensuring national food security and the vulnerability of the system to environmental shocks.

The agricultural sectors in the high-altitude Andean regions of Puno and Cuzco are also exceptionally vulnerable to drought due to their heavy reliance on rain-fed agriculture and the impacts of climate change. In Puno, this vulnerability is starkly illustrated by the significant decline in potato production, which fell from 998,000 tons in 2022 to 596,000 tons in 2023 amid prolonged droughts[33]. This is exacerbated by the fact that approximately 64% of potato cultivation in Peru occurs under rain-fed conditions, lacking access to modern irrigation systems[34].

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The vulnerability of the agricultural sector extends to the Amazonian region of Madre de Dios, which, despite its different climatic context, faces increasing challenges from climate variability. The region is experiencing more pronounced wet and dry seasons, leading to a greater frequency of both floods and droughts, which directly threaten agricultural livelihoods[35]. Small-scale farmers in Madre de Dios are struggling with the impacts of these extreme weather events, often with limited support from national climate change policies[36].

Across the broader Peruvian Andes, populations are highly vulnerable to a future of extreme precipitation and droughts, facing risks from both water scarcity and flooding[37]. This situation is compounded by the fact that many rural communities have limited access to potable water systems, making them even more susceptible to the impacts of water stress on their agricultural activities and daily lives[38].

These forest economies also play a stabilizing territorial role: where forest- dependent livelihoods remain economically viable, pressure for deforestation tends to decrease, contributing indirectly to the maintenance of ecosystem functions such as atmospheric moisture recycling.

Forest economies and rural livelihoods

The forest sectors of Peru and Bolivia are highly vulnerable to small variations in annual climate conditions. Research conducted with local forest communities in Pando, Bolivia, revealed that the effect of climate change that affect their livelihoods the most are temperature increase and drought, with impacts over health and forest resources they depend on[39].

Brazil nut production, which represents a significant forest-based economic activity for rural communities in both countries, requires specific climatic conditions. Brazil nut trees (*Bertholletia excelsa*) depend on consistent precipitation patterns and humidity levels and recent years have demonstrated the sensitivity of productivity to drought[40], with dramatic effects on production levels the following year[41]. In the Madre de Dios region of Peru, around 27,000 people, representing 38% of the population, rely directly or indirectly on the Brazil nut trade for their livelihoods[42]. While it serves as a partial livelihood strategy for many, for some concessionaires, it is their sole source of income, underlining their exposure to declining production levels[43].

These forest economies also play a stabilizing territorial role: where forest-dependent livelihoods remain economically viable, pressure for deforestation tends to decrease, contributing indirectly to the maintenance of ecosystem functions such as atmospheric moisture recycling.

Ecosystems and Species

The sensitive areas of southern Peru and northern Bolivia are characterized by exceptional biodiversity hotspots that have evolved under specific climatic conditions maintained by regional moisture transport patterns. The Tropical Andes are globally recognized as a center of endemism: between 25% and 50% of the species of many taxonomic groups, such as vascular plants, mosses, fishes, and birds, are restricted to this region[44]. A comprehensive analysis by NatureServe researchers of the Yungas of Peru and Bolivia identified 782 endemic species of birds, mammals, amphibians, and plants, many occurring in narrow altitudinal bands[45].


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Relatively small changes in moisture availability could trigger disproportionately large ecological responses, including widespread tree mortality, altered fire regimes, and fundamental shifts in species composition[46]. The biodiversity implications are particularly severe given the high levels of endemism characteristic of these transitional zones between the Amazon Basin proper and the Andean foothills, giving them global relevance for biodiversity conservation objectives.

Furthermore, high Andean wetlands, forests, grasslands, and other habitats are known for their substantial carbon storage capacity due to their low decomposition rates, which result from flooded soils, low temperatures, and low soil pH. These ecosystems, also part of the sensitive areas highlighted, contribute to carbon accumulation and sequestration and play a critical role in mitigating climate change[47]. That role could be lost if precipitation patterns maintained through the atmospheric pathways are disrupted, leading to a feedback loop of carbon emissions and reduced carbon sequestration from biomass.

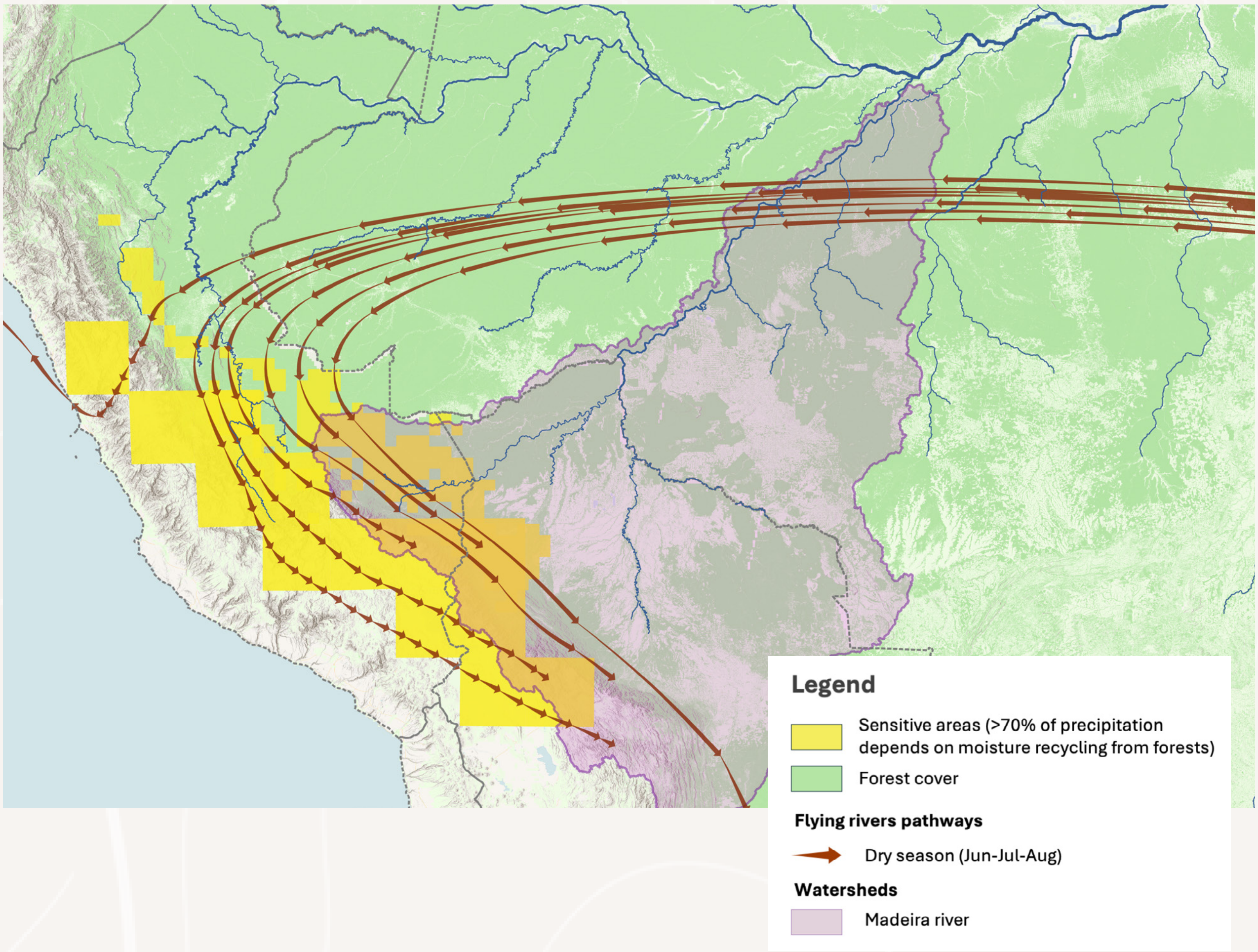
Reciprocal impacts: the Madeira River basin

While the primary direction of environmental dependency flows from Brazil to Peru and Bolivia through atmospheric moisture transport, impacts extend to hydrological systems that ultimately affect Brazilian territories. The flying rivers that transport moisture westward across the Amazon Basin contribute to precipitation patterns that feed river systems flowing Eastward, back toward Brazil.

The Madeira River system exemplifies these reciprocal dependencies. Approximately 60% of the Madeira River discharge where it meets the Amazon, originates from the upper part of its basin, made up of tributaries in Bolivia (Beni and Mamoré rivers) and Peru (Madre de Dios river)[48], making river transport, hydroelectric generation, and flood control systems dependent on precipitation patterns in Peruvian and Bolivian territories (see Figure 4). If atmospheric moisture transport to the southwestern Andean foothills of the Amazon is disrupted by Brazilian deforestation, the resulting reduction in the Madeira River watershed could create downstream impacts that ultimately affect Brazilian infrastructure and economic activities.

The severe drought in the Madeira River basin during 2023 and 2024 triggered profound economic and social consequences, crippling key sectors of the Brazilian economy. The river,

Figure 4. Seasonal pathway to the sensitive areas for the dry season, showing overlap with the watershed of the Madeira River and its tributaries



a major tributary of the Amazon, saw its water level plummet to a historic low of just 25 centimeters in depth at Porto Velho, effectively halting port operations and disrupting the vital transport of grain exports[49 50]. This disruption to inland navigation isolated numerous communities, cutting off their access to essential goods like food, fuel, medicine and drinking water[51]. The crisis also severely impacted Brazil's energy sector, as the drought drastically reduced the output of two of the country's largest hydroelectric plants, which are powered by the Madeira River. This forced a necessary but more expensive shift towards thermal power generation to meet energy demands[52]. The environmental ramifications of the 2023/2024 Rio Madeira drought were equally devastating, creating a cascade of ecological disasters. The unprecedented low water levels led to the mass death of aquatic wildlife, including over 100 river dolphins, a species already under threat[53].

This rapid review, aided by data from the exceptionally severe drought of 2023–2024, highlights the exposure and vulnerability of the southwestern Amazon's peoples, livelihoods and ecosystems to variations in annual precipitation. The best available models of atmospheric water transport over the Amazon all point to the dependency of this area to moisture recycling from dense, mature forests all the way across from the Atlantic Ocean to the foothills of the Andes[54].

Given the compound effects of existing deforestation and climate change, such severe drought events are likely to happen more frequently in the future. Robust climate adaptation strategies will be necessary to mitigate their impacts on the vulnerable communities, economies, and ecosystems of the southwestern Amazon. Alongside adaptation, all available measures should be taken to prevent further loss of flying river functionality.

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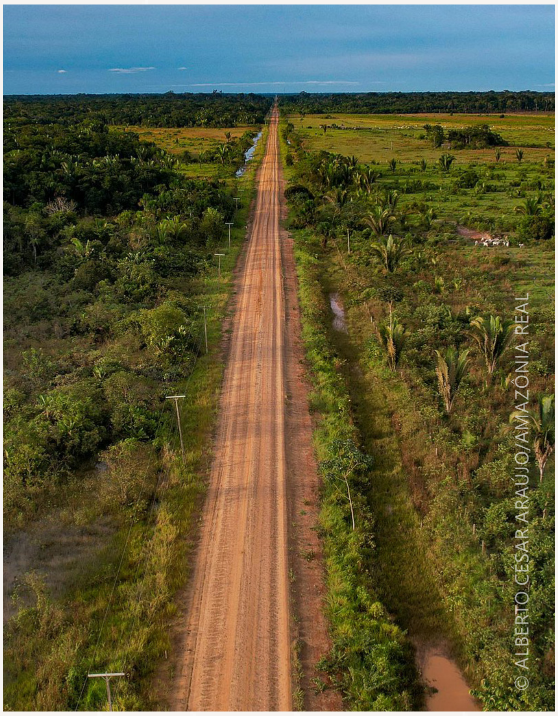
III. Recommendations

A. Environmental and strategic impact assessments that account for impacts on atmospheric moisture transport

As described in Section II, two planned infrastructure developments stand in the path of flying rivers to the southwestern Amazon: the BR-319 and the BR-364. **Regional-scale potential impacts to these flying rivers should be incorporated in the impact assessment studies of these infrastructure projects, highlighting the whole range of potential consequences from their completion, including on the hydrology of the basin**. Strategic Environmental Assessments required for the environmental licensing of road development should also integrate the dimension of potential transboundary impacts to Bolivia and Peru, and the potential for economic and social destabilization of the region. Vulnerable communities and those most dependent on forest resources for their livelihoods should be given particular consideration.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Environmental impact assessments suggest that the completion of the BR-319 could result in up to 5 million hectares of additional deforestation, creating a significant barrier to atmospheric moisture transport. At minimum, any road development should be accompanied by the designation of extensive protected areas along the route, strict measures to prevent side roads that would extend deforestation impacts, and sustainable development programs that provide economic alternatives to deforestation. Undesignated Public Forests along these corridors represent immediate opportunities for protected area designation that could both reduce land-grabbing risk and explicitly safeguard atmospheric moisture pathways as a transboundary ecosystem service.

Beyond direct forest loss, road paving historically triggers broader territorial pressures — including speculative land occupation, land grabbing, illegal logging, and rapid demographic growth in frontier municipalities — that amplify cumulative risks to flying river pathways. This recommendation is especially urgent given the proposed regulatory flexibilization of environmental licensing in Brazil, which risks narrowing the scope of cumulative and transboundary impact assessments in precisely the regions where infrastructure expansion may affect continental-scale hydrological functions.

B. Include contribution to atmospheric moisture transport as a criterion for the designation of new forest conservation areas and funding allocation to existing areas

Systematic conservation planning in the Amazon has traditionally relied on a combination of criteria to identify and prioritize areas for protection. The most common criteria include[55] [56] :

- Biodiversity Value, with a focus on areas of high species richness and endemism,
- Threat Level, with prioritization given to areas under high pressure from agricultural expansion, logging, and other human activities,
- Forest Connectivity, maintaining or improving connectivity between forest fragments,
- Climatic Refuges, identifying areas that can serve as refuges for biodiversity and people under future climate change scenarios, and
- Socioeconomic Factors, such as the location of human settlements, road and river access, and the economic potential of forest resources.

We argue that **the contribution to atmospheric moisture transport should be added to this framework as an explicit sixth criterion**. As Sections I and II demonstrate, the location of forest cover relative to flying river pathways is a determinant of rainfall in the sensitive areas of Peru and Bolivia — a transboundary ecosystem service that existing criteria do not capture. Designating and funding protected areas without regard for their position within moisture transport corridors risks leaving the most hydrologically critical forests unprotected.

A practical tool for operationalizing this criterion would be the mapping of Critical Moisture Territories: areas where atmospheric relevance, deforestation risk, and social vulnerability overlap. These spatially explicit zones could guide the integrated prioritization of conservation designation, restoration funding, and sustainable development investments, ensuring that moisture transport continuity from the Atlantic to the Andes is treated as a core objective rather than a secondary benefit.

The most urgent application of this criterion is the designation of Undesignated Public Forests (UPFs). These approximately 50 million hectares of Brazilian Amazon territory remain under federal or state government ownership but lack any formal legal classification — they are neither protected areas nor concessions or land grants[57]. As Section I showed, UPFs account for some of the most exposed gaps in the flying river pathways, particularly along the dry season route through the central Amazon. Their regulatory gray zone status leaves them vulnerable to illegal logging, land invasions, and speculative land grabbing — between 26% and 30% of annual deforestation in the Brazilian Amazon is estimated to occur in UPFs, largely through actors illegally using the Rural Environmental Registry (CAR) to claim ownership[58]. A 2023 analysis in Nature Communications[59] found, based on 33 years of data, that any formal land tenure regime — including private ownership — reduces deforestation more effectively than leaving lands undesignated. Formal designation as protected areas, particularly where it coincides with Critical Moisture Territories, is therefore both the most direct way to reduce land grabbing and the most effective tool for securing the hydrological continuity of flying river pathways.

Designation alone, however, is not sufficient. In many parts of the Brazilian Amazon, forest permanence depends less on legal status than on whether communities have a viable economic stake in keeping forests standing. Legal protection needs to be accompanied by governance arrangements that secure territorial presence and support forest-based livelihoods — through sustainable development reserves, community forest concessions, non-timber forest product chains, agroforestry, and other arrangements that reduce pressure for land conversion while generating local income.


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The global policy context offers a strong mandate for action. The Kunming-Montreal Framework's Target 3 (30×30) aims to protect 30% of terrestrial and inland water areas by 2030, and Brazil's National Biodiversity Strategy and Action Plan sets a target of 80% of the Amazon under some level of protection, meaning significant further designation can be expected. This momentum creates a window of opportunity: if moisture transport corridor continuity is factored into how these new areas are selected, the 30×30 agenda can deliver biodiversity outcomes and hydrological security simultaneously. If it is not, vast areas may be designated in ways that fail to protect the atmospheric pathways on which Peru and Bolivia depend. Designation and funding processes should therefore explicitly account for each area's role in maintaining flying river functionality, using the Critical Moisture Territories framework as a spatial guide.

The financial vehicles to support this are already mobilizing. The Amazon Region Protected Areas (ARPA) program has designated 128 million acres to date, with a remaining target of 22 million acres[60]. With the reactivation of the Amazon Fund in 2023, BNDES has mobilized an additional R$ 3.4 billion for forest conservation and restoration[61]. The newly created Tropical Forests Forever Fund (TFFF) is also poised to provide a long-term funding stream to conservation units. Integrating atmospheric moisture transport as a criterion into these programs' allocation decisions would help ensure that funding flows to the areas where forest protection delivers the greatest hydrological benefit — for Brazil and for its Andean neighbors alike.

C. Accelerate restoration along the flying river pathways

While this report focuses on deforestation risk in the western Brazilian Amazon, the path of the flying rivers during the dry and transition seasons also crosses vast areas of the eastern Brazilian Amazon that have already been heavily deforested.

The southeastern Amazon, particularly the heavily deforested areas of southern Pará state, is a key target for large-scale forest restoration to recover atmospheric moisture pathway functionality. Recent initiatives such as BNDES's Restaura Amazônia program, framed within Brazil's PLANAVEG target of restoring 12 million hectares by 2030, are an important first step. However, given the critical role of this region in sustaining moisture transport, **investments need to be substantially scaled up, strategically targeted on key hydrological corridors, and integrated with climate and land-use policies to effectively recover regional moisture recycling and stabilize downwind rainfal**l.

Restoration strategies should prioritize degraded areas where ecological recovery can be combined with productive forest-based systems, including agroforestry and community restoration economies, increasing both permanence and social feasibility.

In transition zones between forest and agricultural land, agroecological systems can also function as adaptation strategies by improving soil moisture retention, diversifying production, reducing dependence on monocultures and maintaining partial evapotranspiration functions in productive landscapes.

D. Build regional governance that reflects Brazil's outsized responsibilities

The absence of regional governance over forest cover in the Amazon is a critical vulnerability for Peru and Bolivia. Brazil controls approximately 60% of the Amazon Basin and sits between the Atlantic Ocean and the Andean foothills, meaning that through the removal or protection of its forest cover it exerts near-total control over the fate of the flying rivers that bring moisture to Andean countries. Yet the current governance frameworks for addressing transboundary environmental dependencies in the Amazon are inadequate to the scale of this asymmetry. The Amazon Cooperation Treaty Organization (ACTO)'s consensus-based decision-making structure, for example, creates systematic obstacles to effective action by granting veto power to any single member state.

The Belém Declaration, adopted at the 2023 ACTO heads-of-state summit, marked a step forward by committing member states to avoiding the Amazon's tipping point. However, it fell short on two counts: it did not establish differentiated responsibilities that reflect Brazil's outsized influence on atmospheric moisture transport, and it set no quantitative deforestation targets by country, making it impossible to assess progress or hold governments accountable. **Advancing regional governance will require moving beyond this baseline toward frameworks that acknowledge asymmetric dependencies, set spatially explicit conservation objectives, and build in mechanisms for monitoring and enforcement**.

Concretely, this means pursuing two complementary tracks:

- Developing differentiated responsibility frameworks within ACTO that formally recognize the asymmetric environmental dependencies within the Amazon Basin. Brazil's outsized role requires the acceptance of enhanced obligations for maintaining atmospheric moisture transport corridors that sustain forests and economies in neighboring countries.
- Formalizing these responsibilities through binding bilateral or multilateral agreements — modeled on existing transboundary water management frameworks for shared waterways and catchment areas — that establish specific obligations for Brazil to maintain forest cover in areas critical for moisture transport to Peru and Bolivia, whether through the protection of defined moisture transport corridors or the conservation of minimum forest cover thresholds within identified "precipitation catchments."

E. Develop climate adaptation strategies for the sensitive areas

Ecosystem-based adaptation measures have been recommended for the department of Pando in Bolivia, such as diversification of economic activities based on Amazon fruits, agroforestry systems, freshwater management and forest restoration[62]. The vulnerability of the region to a breakdown in flying river transportation highlights the importance of extending such assessments to other departments — including Northern Beni, Santa Cruz, and La Paz — that may also be affected by more frequent and intense drought events. Given the cross-border nature of the flying river system, **these strategies** should be developed in coordination with Brazil and Peru, and **should explicitly account for the risk of reduced atmospheric moisture transport alongside other climate-related stressors.**

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F. Advance the research agenda

The recommendations above rest on a rapidly evolving scientific base. The following research priorities would strengthen the evidentiary foundation for policy action and reduce key uncertainties:

- Modeling of the effects of large-scale restoration in the southeastern Amazon on dry season pathway functionality, taking into account future climate change. The result of this exercise would be a quantified assessment of how different restoration scenarios could improve moisture transport capacity and reduce drought vulnerability in Peru and Bolivia under various climate change projections.
- Refining the mapping of atmospheric moisture transport corridors using advanced atmospheric modeling techniques that account for seasonal variations in moisture transport patterns, topographical influences on atmospheric circulation, and the cumulative impacts of multiple deforestation sites. The effects of localized forest cover loss should be modeled to provide quantitative estimates of the potential loss of precipitation over the sensitive areas.
- Modeling the effects of projected climate change on the seasonal pathways themselves: areas where moisture pathways are likely to shift in the future should be identified and prioritized for protection, even if they are not currently critical for existing routes.
- Expanding monitoring networks and modeling efforts for “reciprocal watershed and precipitation-sheds”, including expanding river flow and precipitation monitoring stations across the Amazon basin, and improving atmospheric and hydrologic models to quantify the relationships between moisture transported by flying rivers and surface water flow in major rivers like the Madeira. Better-calibrated models would allow researchers to develop more robust drought risk assessments — from reductions in precipitation to reductions in river level — providing stronger evidence for climate adaptation planning in vulnerable communities.
- Reducing key uncertainties in the relationship between Amazon deforestation and the regional climate system, including the effects on the hydrological cycle and Atlantic–Amazon–Andes connectivity[63]. While the loss of Amazon forest is already associated with reduced evapotranspiration, altered circulation patterns, and delayed wet season onset,[64] [65] these dynamics interact with broader global climate shifts[66] [67], in ways that remain incompletely understood[68]. Strengthening research capacity in Amazonian countries — including enhanced monitoring systems, improved biophysical–atmospheric modeling, and early warning systems — is essential to narrow these uncertainties and build the evidence base for policy[69] [70] [71] [72].

Conclusion

Forests are the engine of the Amazon's water cycle. Through evapotranspiration, they continuously recharge the atmosphere with moisture, enabling flying rivers — vast atmospheric flows that carry water from the tropical Atlantic across thousands of kilometers of forests to the foothills of the Andes. The forests and communities of the southwestern Amazon in Peru and Bolivia depend on this process for over 70% of their annual rainfall.

This white paper has mapped, for the first time with seasonal resolution, the pathways through which this service is delivered — and the points at which it is most exposed to disruption. The dry season pathway, which is both the most critical for moisture recycling and the most dependent on intact forest, already flows over heavily degraded land in southern Pará and is directly threatened by the imminent paving of the BR-319, which could trigger up to 5 million hectares of additional deforestation. The transition season pathway crosses vast stretches of undesignated public forests that lack the legal protection needed to prevent eventual conversion. The wet season pathway currently benefits from relatively robust protection, although before reaching Peru and Bolivia, all three pathways converge over the State of Acre, where multiple road development projects could disrupt year-round moisture transport.

The exposure assessments in Section II make clear what is at stake. The 2023–2024 Amazon drought — the most severe on record — showed what that disruption looks like in practice, with drastic consequences for local economies and ecosystems. While that event cannot be attributed solely to deforestation, it shows the scale of harm that a sustained disruption could cause. Through deforestation, policy decisions in Brazil directly impacts the flying rivers on which these countries depend, yet current governance frameworks provide no mechanism to reflect that responsibility.

This calls for spatially targeted conservation, credible regional governance, and the recognition of a new dimension in arguments to reduce deforestation: that even localized loss of vegetation cover can have potential impacts on communities and ecosystems beyond national borders.

Annex I
Methodological notes

To visualize moisture transport pathways across the three seasons, we use data from the ERA5 reanalysis for the period 2001-2020. This time period is appropriate as it captures (i) the intensification of extreme weather events already caused by climate change and (ii) potential effects of recent deforestation.

The ERA5 variables used are *viwve* - Total column vertically-integrated eastward water vapour flux, *viwvn* - Total column vertically-integrated northward water vapour flux and *ivt* - Magnitude of the vector flux. To convert these flux fields into streamlines, we built interpolation functions from the regular latitude–longitude grid and defined a velocity field by transforming flux values into angular velocities (degrees per second), accounting for Earth’s radius and latitude-dependent grid spacing. Backward streamline integration was then performed using the Runge–Kutta 45 (RK45) method, starting from 680 seed points on a 1.5° × 1.5° grid across the Amazon basin and tracing each trajectory backward in time to identify where the moisture originated. This approach follows the method used in Santiago et al. (2025).

To identify the areas most vulnerable to disruptions of transpiration-based moisture recycling, we combined the spatially explicit outputs of two studies[73]. Weng et al. (2018) covers both the dry and wet seasons and defines “sensitive areas” as those where more than 50% of rainfall originates from Amazonian evapotranspiration — the 98th percentile of sensitivity to Amazonian land use change. Staal et al. (2018) focuses on the dry season and estimates the effect of Amazon tree transpiration on forest resilience; we selected areas with a resilience loss fraction of 0.8 or higher, representing the proportion of resilience that would be lost in the absence of tree transpiration. Merging these two datasets allowed us to identify, across seasons, the areas where rainfall is most dependent on Amazonian forest cover remaining intact.

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