Looking upstream: analyzing the protection of the drainage area of Amazon rivers

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Key Points:

- We provide accumulated deforestation, mining, and protection across the Amazon river network
- 50% of the Amazon rivers have less than 1% deforestation upstream, and 5% have some upstream mining area
- While about 40% of the Amazon basin is under some protection, 50% of the Amazon rivers are unprotected because the delimitation of the PA does not cover its upstream drainage areas.

Abstract

In the Amazon, aquatic ecosystems provide essential ecosystem services, including transportation, food, and livelihoods for millions of species. Land use changes and management impact these ecosystem services, and these impacts are not limited to the specific areas where they occur but propagate downstream along the drainage network. However, assessment of the accumulated human footprint upstream of Amazonian rivers has been largely overlooked. Here, we provide explicit spatial information on accumulated deforestation, mining, and protection across the river network. We aim to indicate the most impacted rivers and where the consideration of the watershed concept could improve the security of Protected Areas, including Indigenous Lands, in the Amazon. Our results show that 50% of the Amazonian rivers are pristine (less than 1% deforestation upstream), and 5% have some upstream mining area. However, while about 40% of the Amazon basin is under some protection, almost half of the rivers are, in truth, unprotected because the delimitation of the protected area does not cover its upstream drainage areas. Finally, our analyses identify hotspots of accumulated deforestation and mining and highlight the potential vulnerability of the rivers within protected areas due to upstream deforestation, allowing decision-makers to rethink the conservation status of the Amazonian aquatic ecosystems.

1 Introduction

Although it constitutes only 0.001% of the Earth's water (Thomas, 1994), river water provides critical services such as water provisioning for drinking and nondrinking uses, food provisioning (e.g., fisheries), recreation, and maintenance of biodiversity (Grizzetti et al., 2016). Rivers are vital to conserving and sustaining freshwater ecosystems, which are home to 10% of all Earth species, with high fragmentation and endemism (Strayer & Dudgeon, 2010). However, population trends for monitored freshwater species indicate a steep decline, which could be attributed to human activities that affect the quantity and quality of freshwater, the habitat of freshwater species and the biodiversity (eg.: overexploitation) (WWF, 2022).

Before reaching the rivers, rainwater flows over the Earth's surface, interacting with it, and its quantity and quality are affected by land use and land cover. Pollution from diffuse sources and environmental degradation are the leading causes of river problems and are the most difficult to solve (Grizzetti et al., 2016). Climate and land use and cover changes, human alteration in riverbanks (Wu et al., 2023), and water withdrawal can also impact water quantity and change the seasonality of river flow regimes across the whole drainage network, largely stressing rivers (Nations, 2002) and their biodiversity (Magoulick et al., 2021). Human activities can be felt downstream from where these activities take place, even in distant locations (Castello et al., 2013; H. Munia et al., 2016; Veldkamp et al., 2017).

Despite their importance, existing management policies have failed to account for the hydrological connectivity of freshwater ecosystems (Castello et al., 2013; Reis et al., 2019). For instance, although the creation of protected areas (PAs) is one of the most common actions taken to protect biodiversity, actual PAs are not sufficient to conserve freshwater biodiversity because they do not consider the watershed concept in their delineation process (Acreman et al., 2019). The watershed is the natural catchment area of rainwater that routes runoff into a single point in the river.

In the Amazon, ongoing changes directly (e.g., livestock and agricultural expansion) or indirectly (e.g., climate change, lack of governance, illegal activities, and population increase) linked to deforestation threaten the region’s vital role in global climate and biodiversity (Albert et al., 2023). Deforested areas are mainly converted into pastures, although an increase in agricultural areas has been seen in the southern Amazon in recent decades (Maciel et al., 2020). Even though increases in PAs have reduced deforestation within their boundaries and in their surrounding areas (Fuller et al., 2019; Herrera et al., 2019; Qin et al., 2023), their river networks carry an upstream landscape footprint, which can threaten the integrity of freshwater ecosystems (Abell et al., 2016). Therefore, it is crucial to plan PAs not only from a terrestrial ecosystem viewpoint, but also from a freshwater ecosystem and catchment-based perspective (Leal et al., 2020)

Location-specific data can better support decision-making if data collection, analysis, and visualization are designed to target decision-making needs (WEF, 2022). However, current land use and land cover spatial databases are typically provided per pixel or accumulated at administrative levels (e.g. municipalities (Rorato et al., 2023)), which do not consider the natural watershed limits. Only recently have databases started providing information on land cover change according to the hydrographic basins of large rivers, unit catchments, or river reaches (Linke et al., 2019; Venticinque et al., 2016). The total land use of a basin may not reflect the distribution of this land use along its drainage network and may have hotspots of low water resource conservation status that are undetectable without assessing upstream conditions.

Here, we provide a new understanding of the conservation status of Amazon water resources from a cross-scale perspective, from upstream to downstream directions and along complex drainage networks. We use global river network and PA, including Indigenous Lands, datasets and other South American environmental geospatial datasets to generate accumulated landscape metrics (deforestation, mining and protection) for the entire river network, about 1.5 million km of rivers, and depicting the percentage of deforested, mined, and protected area upstream (in the drainage area) of each 500 m river pixel along the entire Amazon. We also conduct a complementary analysis considering only the river reaches within PAs. We provide evidence that we are not looking at the river basin when thinking about Amazon conservation, ultimately aiming at improving the sustainable planning and management of the waters of the largest river basin on Earth.

2 Materials and Methods

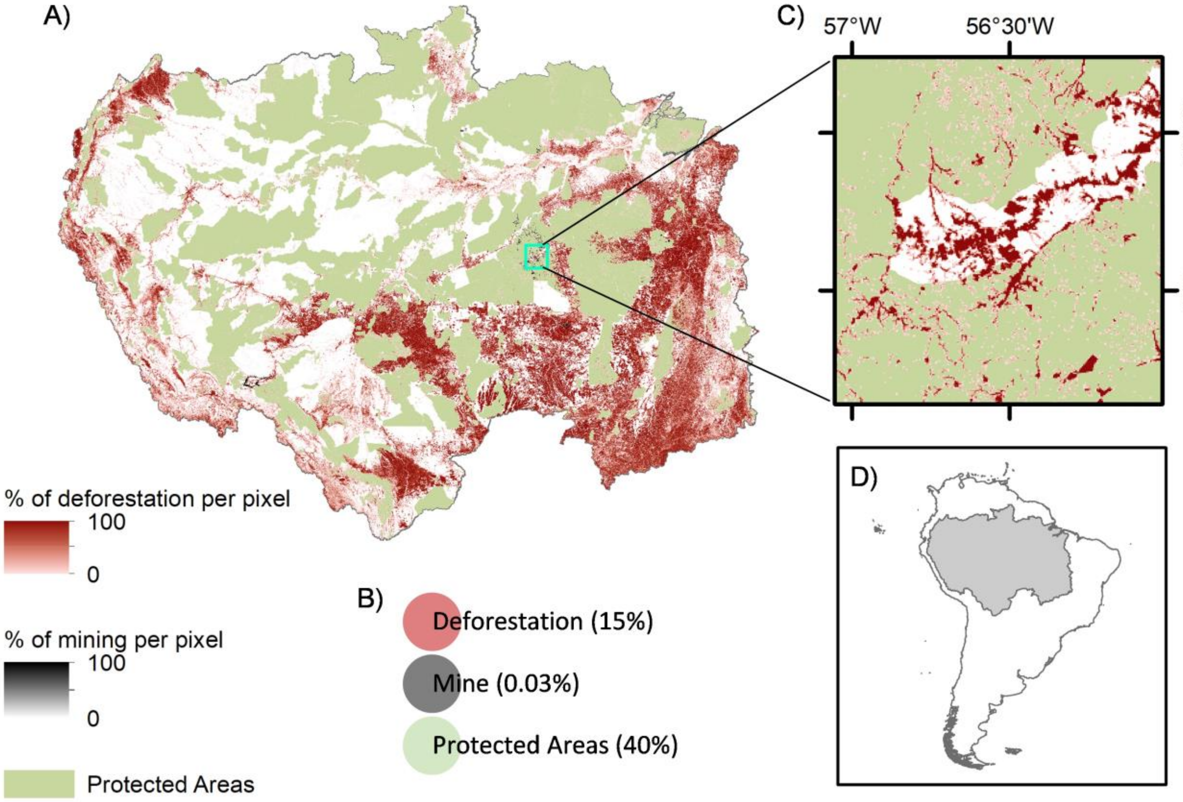
2.1 Datasets and data processing

We analyze land use and land cover along Amazonian rivers based on several datasets. The adopted Amazon Basin limit is the one provided by the HydroSHEDS level 2 basin product (Lehner et al., 2008), which includes the Amazon and Tocantins-Araguaia basins. We used the global HydroSHEDS products (Lehner et al., 2008) at 15 arcsec spatial resolution, which is based on elevation data obtained in 2000 by NASA's Shuttle Radar Topography Mission (SRTM). HydroSHEDS provides georeferenced hydrographic information at various scales, including river networks, watershed boundaries, drainage directions, and flow accumulations.

The deforestation and mining areas in 2020 (Figure 1) were obtained from the MapBiomas Amazon Project Collection 3 Project43, which is a multi-institutional initiative to generate annual land use and land cover maps for the region based on automatic classification of satellite imagery. All non-natural land use and land cover classes were reclassified as deforestation areas and reprojected and downgraded to the Hydrosheds pixel resolution. For this process, we calculated the fraction of each Hydrosheds pixel that is covered by the 30 m deforested pixels and multiplied the results by the Hydrosheds pixel areas. The MapBiomas project considers mining as all areas of extraction of minerals with soil exposure without differentiating the type of mining (industrial, artisanal, or illegal).

The location of Amazon PAs (Figure1a) was obtained from the World Database on Protected Areas (WDPA, 2012), which is updated monthly and managed by the United Nations Environment Programme's World Conservation Monitoring Centre. There are many overlapping PAs in the WDPA with different categories and designations (national, regional, and international PAs). The WDPA are used for reporting to the Convention on Biological Diversity on progress towards reaching the Aichi Biodiversity Targets and other international assessments and reports. We maintained all the PAs with the status “designated” in the database, including overlaps, all PA management category and governance type. Some results are discussed by PA groups, including the most (I to IV) and less (V and VI) strict IUCN protection categories, indigenous land, and others. All these types are important for Amazonian forest conservation (Qin et al., 2023; Nolte et al., 2013), although strictly protected areas and indigenous land commonly avoiding more deforestation than sustainable use areas (Nolte et al., 2013).

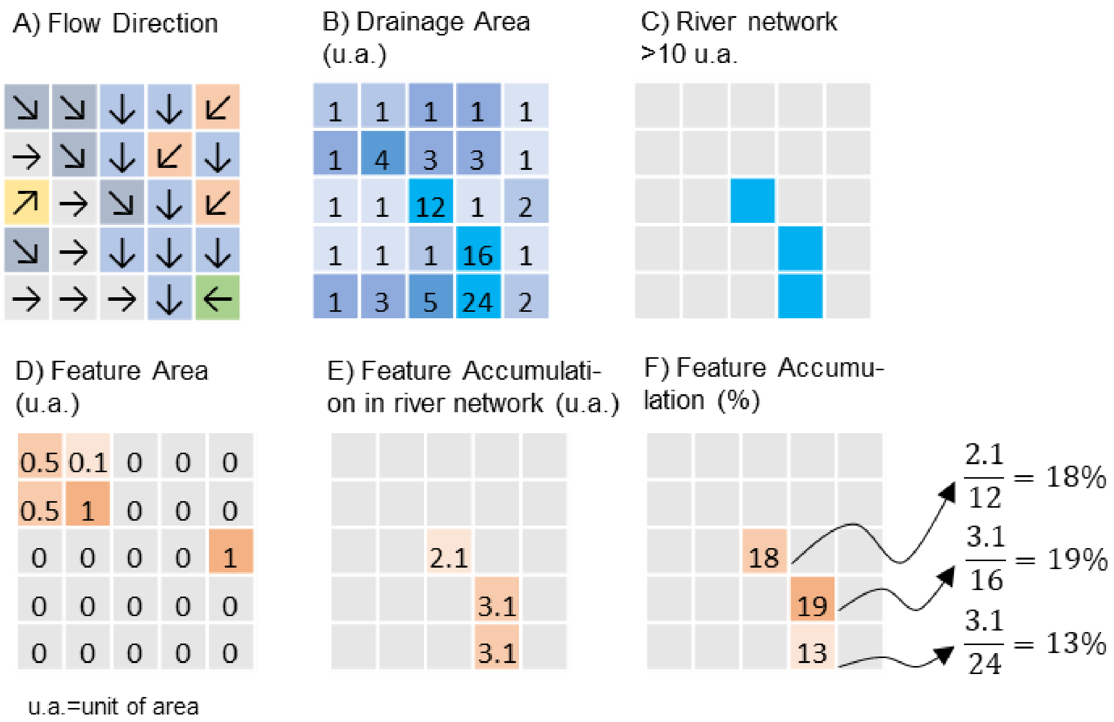
Figure 1. a. Deforested and mining areas per 15-arc-second pixel and protected areas, with **b.** the percentage of each of these land uses in the Amazon, **c.** a zoom in an area with intense mining activity. **d.** Location of the study area in South America.



2.2 Land use type accumulation along the drainage

From the 15 arc-second (~500 m) flow direction matrix (Figure 2a), we calculated the upstream area for each pixel (flow accumulation) (Figure 2b). The next step was to identify the river network, which is considered the channelized river (Figure 2c). For this step, a threshold of 20 km² on the flow accumulation matrix was applied to determine the beginning of the river network.

Figure 2. a. Hypothetical representation of the steps to the calculation of feature accumulation from: a. flow direction, **b.** upstream drainage area, **c.** river network definition, **d.** feature area, **e.** feature accumulation, and **f.** percentage of the feature in the drainage area of each river network pixel.



A similar method was used to compute the accumulated area occupied by each land use type upstream of the drainage pixel. The value of each feature (deforested/mining/PAs) accumulated in a pixel is equal to the sum of the values of the feature areas in all pixels that drain to it, based on their flow direction information (Figure 2d and Figure 2e). The final step was to determine the percentage between each land use accumulated and contributing area for each river network pixel (Figure 2f).

2.3 Data analyses

We presented the results by river pixel and subbasins (basin level 5 defined by Hydrosheds). We generated approximately 1.462 million river pixels for Amazon, and different categories of river reaches were defined according to land use and contributed area ratio:

- Pristine: river pixels with less than 1% of deforestation in their catchment area.
- Near total deforested: river pixels with more than 90% deforestation in their catchment area.
- Totally protected: river pixels with more than 99% of their catchment area within PAs.
- Unprotected: river pixels with less than 1% of their catchment area inside PAs.
- With upstream mining area: River pixels with one or more pixels classified as mining areas in their drainage network, even though drainage from mining areas can be collected and directed to specific dams.

Then, we calculated the percentage of the drainage pixels classified in the above classes, as well as the maximum and minimum values of the accumulated landscape metrics, using the Zonal Statistics function of QGIS (QGIS Geographic Information System; http://www.qgis.org) per each of the 109 Hydrosheds 5-level basins (mean of approximately 63,000 km²) and per each of the 1195 protected areas (mean of approximately 3,054 km²). We highlight examples of basins and protected areas with the best and worst results.

2.4 Looking upstream in a highly complex subbasin

To illustrate the variation in the accumulated deforested/mining/protected areas along a river network of one specific 5-level basin, we chose the Itacaiúnas river basin. This basin is located in the eastern Amazon (Figure 2a), and has an interesting combination of deforestation, mining activities, and protected areas. The Itacaiúnas River is a direct affluent of the Tocantins River, and its basin is approximately 41,000 km². From the 1980s to 2010s, the land use in the basin has dramatically changed, with the forest areas being replaced mostly by pasture (Souza-Filho et al., 2018). Currently, almost half of the basin is deforested, with most of the preserved areas concentrated in a set of conservation units and indigenous land located in the western part of the basin, commonly called the Carajás Mosaic of Protected Areas. The Carajás mineral province has numerous metal ore deposits, with several active mines, including the largest open-pit iron ore mine in the world, which is located within one of the protected areas of Itacaiúnas River Basin.

2.5 Methodological limitations

Recognizing the importance of longitudinal and lateral connectivity is necessary to promote the conservation of the Amazon's social and biodiversity (Reis et al., 2019). The accumulated land use along the rivers calculated in this study considers the longitudinal connectivity downstream of rivers. Nevertheless, there are also impacts that propagate upstream due to the river continuum by the mobility of the fauna or due to backwater effects and lateral connection during flood events, among others (Meade et al., 1991)

The final results reflect the uncertainties of the selected datasets: Mapbiomas and Hydrosheds. For example, Mapbiomas is a project to provide land use and land cover classification for all of Brazil and Amazon. Illegal mining activities, for example, may be underestimated. The study case in the Itacaiúnas River basin, when compared with other studies (Nunes et al., 2019) and with satellite images of the area, appears to overestimate the deforestation within the PAs. Due to pixel size, deforestation and mining values within small protected areas calculated with Zonal statistics may have significant errors. The results will be refined in future updates of the database indicated in the Data Availability section.

The flow direction of the area is determined by the topography, according to a digital model of the hydrological transformation of the watershed. Therefore, drained alterations are not considered, as they may occur in mining areas due to a change in topography or to prevent mining areas from draining directly into rivers. Additionally, since we analyzed only rivers with a minimum drainage area of 20 km², the results cannot reflect the conditions of smaller headwaters. The results by PA, especially in the case of small PAs, are influenced by the rivers on their borders that may or may not be considered within the PA, depending on pixel position.

4 Results

4.1 Upstream deforestation, mining, and protection through the Amazonian rivers

In 2020, 15% of the Amazon basins (about 7 million km²) was mapped as deforested areas, concentrated in the eastern and southern Amazon, a region known as the Brazilian arc of deforestation. Deforestation in the analyzed subbasins represents 0% to 71% of their total areas (Figure 3a). However, even considering only the main rivers (order equal to or greater than five), it is possible to see a great spatial variation in the percentage of the accumulated upstream deforestation along the river network (Figure 3a). For example, while 12% of the 5-level subbasins have deforestation levels of less than 1%, approximately 50% of the river pixels are in this category (hereafter called pristine rivers) when looking at the entire upstream drainage area (histogram in Figure 1a). Most of the subbasins with a high percentage of pristine rivers are located on the left bank of the Amazon River, in the northern portion of the basin.

On the other hand, 1% of the river pixels have deforestation levels of more than 90% in their upstream areas (bar chart in Fig. 3a), located mainly along the arc of deforestation; these are hereafter considered near total deforested pixels. The Itacaiúnas River basin (highlighted in blue in Figure 4a, and discussed in section 4.3), in the eastern Amazon, presented the highest percentage (14% of its river network was classified as near total deforested), followed by the Araguaia River, upstream from the confluence with the Tocantins River (8%), and the Ji-Paraná basins (6%).

In 2020, mining areas corresponded to 0.03% of the Amazon. The proportion of mining areas per level-5 subbasin varies from 0% to 0.81% (Figure 3b). Regarding the river network, 5% of the river pixels have some upstream mining areas. Although the mining activity across the Amazon is small compared to other land uses, for some river pixels, up to 70% of the upstream area is affected by mining, such as those in the Itacaiúnas River basin in the eastern Amazon (section 4.3). In the middle Tapajós and Crepori subbasins, 37% of the river network has some mining in their drainage area (Figure 4b).

Approximately 40% of the Amazon basin is under some protection. There are 1063 already designated protected areas, including 231 PAs classified as IUCN category I-IV, 386 V-VI, 318 indigenous land and 128 classified as other types. At the local scale, only 8% of the subbasins are unprotected (have less than 1% of their area under protection) (Figure 3c). However, when we look at the entire river network, 46% of it is classified as unprotected (histogram in Figure 3c), primarily because of small rivers. The subbasins with the lowest percentage of protection and those with the highest rate of unprotected river network are within the Tocantins-Araguaia River basin, in the eastern Amazon, and Tapajós basin, in the south of Amazon. For the right-bank tributaries of the Amazon River, a northward increase in protection is observed; for instance, more than 80% of the river network of the Upper Rio Teles-Pires Basin (a tributary of the Tapajós River) was classified as unprotected (Figure 4c).

Figure 3. a. Deforested, **b.** mining, and **c.** protected areas (in %) of each level-5 Amazon sub-basin and the upstream deforested, mining, and protected area (in %) of each pixel in the river

network with order equal to or greater than 5. The figures also show details illustrating the upstream deforested, mining, and protected areas (in %) of each pixel in the river network mapped (drainage area up to 20 km²) and the histogram of the deforested, mining, and protected areas for the order-5 subbasins and for the entire river network.

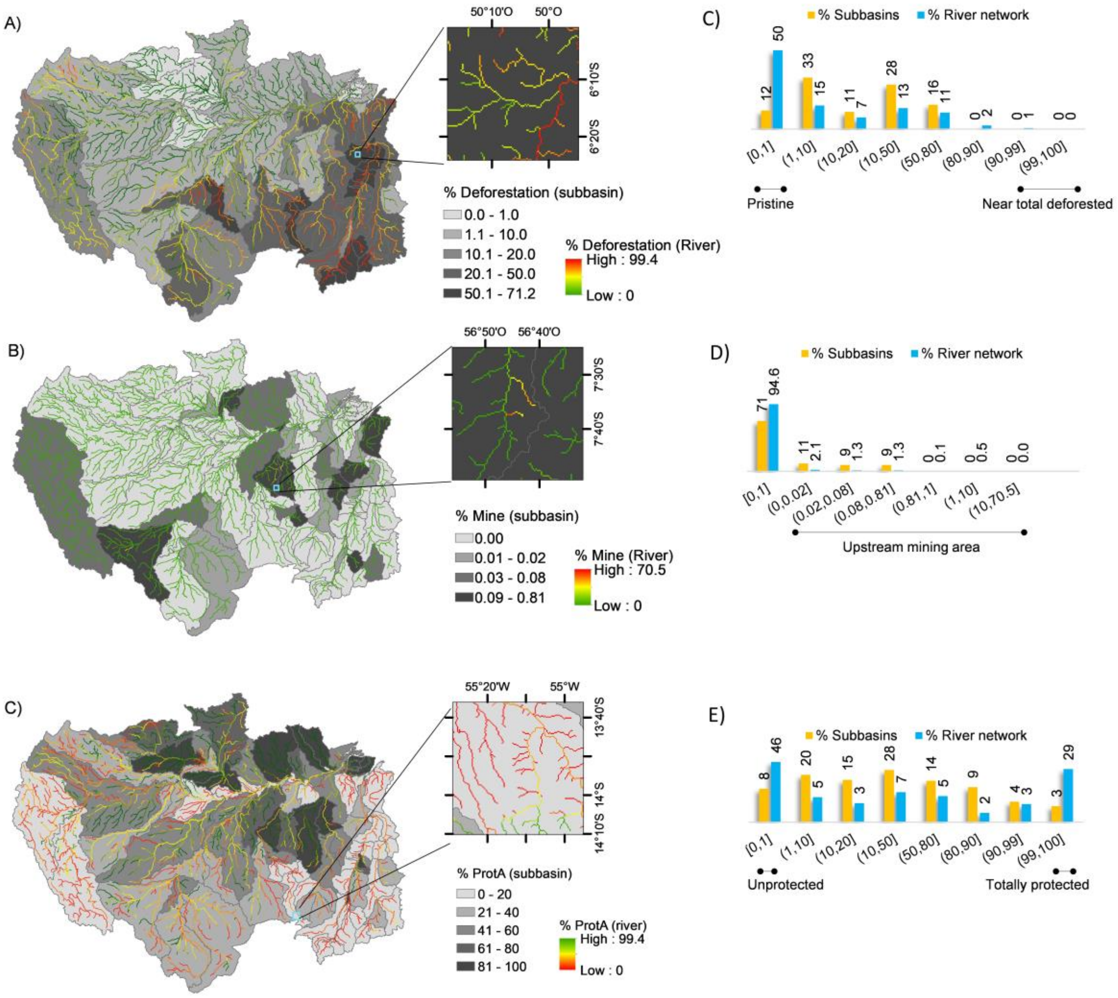
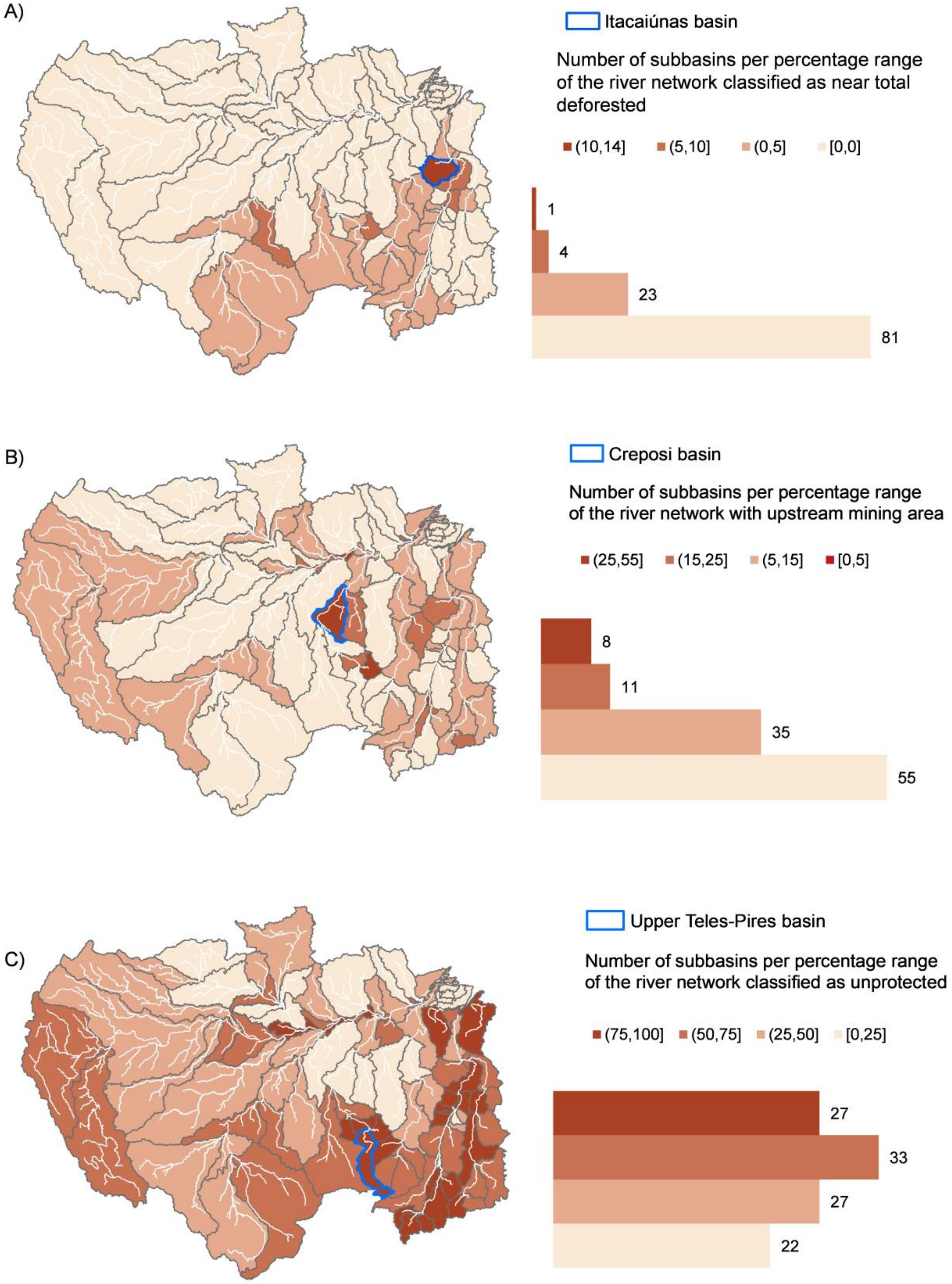


Figure 4. Percentage of river pixels in each Amazon level-5 basin classified as **a.** near total deforested (pixels with more than 90% of its drainage area deforested), **b.** with upstream mining area, and **c**. unprotected (river pixels with less than 1% of its catchment area within PAs).


A)
Itacaiúnas basin
Number of subbasins per percentage range of the river network classified as near total deforested
(10,14]
(5,10]
(0,5]
[0,0]
1
4
23
81
B)
Creposi basin
Number of subbasins per percentage range of the river network with upstream mining area
(25,55]
(15,25]
(5,15]
[0,5]
8
11
35
55
C)
Upper Teles-Pires basin
Number of subbasins per percentage range of the river network classified as unprotected
(75,100]
(50,75]
(25,50]
[0,25]
27
33
27
22

The most protected subbasins are those located on Marajó Island since the island is within conservation units for sustainable use. Approximately 80% of the river reaches of the Jari, Paru, and Trombetas rivers are totally protected (more than 99% of their drainage area is under protection). These rivers are left-bank tributaries in the lower Amazon, with headwaters on the border of Brazil and Suriname, French Guiana, and Guyana. Most protected areas are integral protection conservation units (strict nature reserves in IUCN classification) and indigenous lands. Despite the high degree of deforestation in the Upper Xingu River, the Iriri River, the main tributary in its middle portion, has a high degree of protection in its upstream areas (Fig 4c). Around 78% of its river network is totally protected, but there are river pixels in some small tributaries for which 21% of their drainage area is deforested.

4.2 The conservation status of the river networks within protected areas

Considering the land use in all Amazon designated PAs (total of 2,7 million km²), 0.03% is mining areas (742 km²), ranging from 0 to 3.4% of mining area per PA, and only 2.1% is deforested (58,000 km²) (Figure 5a and b). In 14 PAs, more than 90% of the area is deforested, most with less than 1 km². The Civil Society Nature Reserve Hacienda Villa Mery (IUCN category VI) is an exception as it has 9.6 km², of which 99.7% is deforested.

Within Amazon PAs, 78% of the river network is pristine (less than 1% upstream deforestation). The percentage is higher for the most restrictive IUCN categories (I-IV, 82%) and Indigenous Land (81%), then other categories (75%). Similarly, 77% have totally protected upstream areas, reaching 81% in PA’s categories I-IV and 79% in indigenous land. Results vary significantly between PAs; the whole river network within some PAs is totally protected or pristine (Fig. 5a and Fig. 4e). In contrast, other PAs contain no river pixels in these categories (Figure 5f). In 94 PAs (of the 862 with assessed river pixels), the entire river network was classified as pristine (Fig. 6a). Of that, 40 are designated Indigenous Lands. These PAs are primarily located in the northern region, as the part of the Alto Orinoco – Casiquiare Biosphere Reserve (IUCN category V, protected landscape) and the Paríma – Tapirapeco National Park (IUCN category II), all in Venezuela, and located in the eastern Amazon basin, as the Alto Purus National Park (IUCN category II), in Peru. The boundaries of these PAs partially follow the watershed limits (see detail in Figure 7c for the Alto Purus), which helps river protection: 94%, 98%, and 92% of their river networks are totally protected. In 37 PAs, the entire river network is classified as totally protected (Figure 6e), indicating that most of the watershed, not only the terrestrial area, is protected. These areas include 6 indigenous lands. Furthermore, the protection status does not guarantee pristine rivers, as there are 13 PAs with all river networks classified as totally protected but no river pixels classified as pristine.

Figure 5. a. Deforested area (in %) of each protected area (PA) in the Amazon and the upstream deforested (Def.) area (in %) of each pixel in the river network with an order equal to or greater than 5. **b.** The same for mining areas, and **c.** protected areas. The PAs highlighted in the zoom are the a. proposed Ponte de Pedra indigenous land, b. Tapajós, and c. Alto Purus National Park. Due to overlaps, not all protected areas can be visualized.

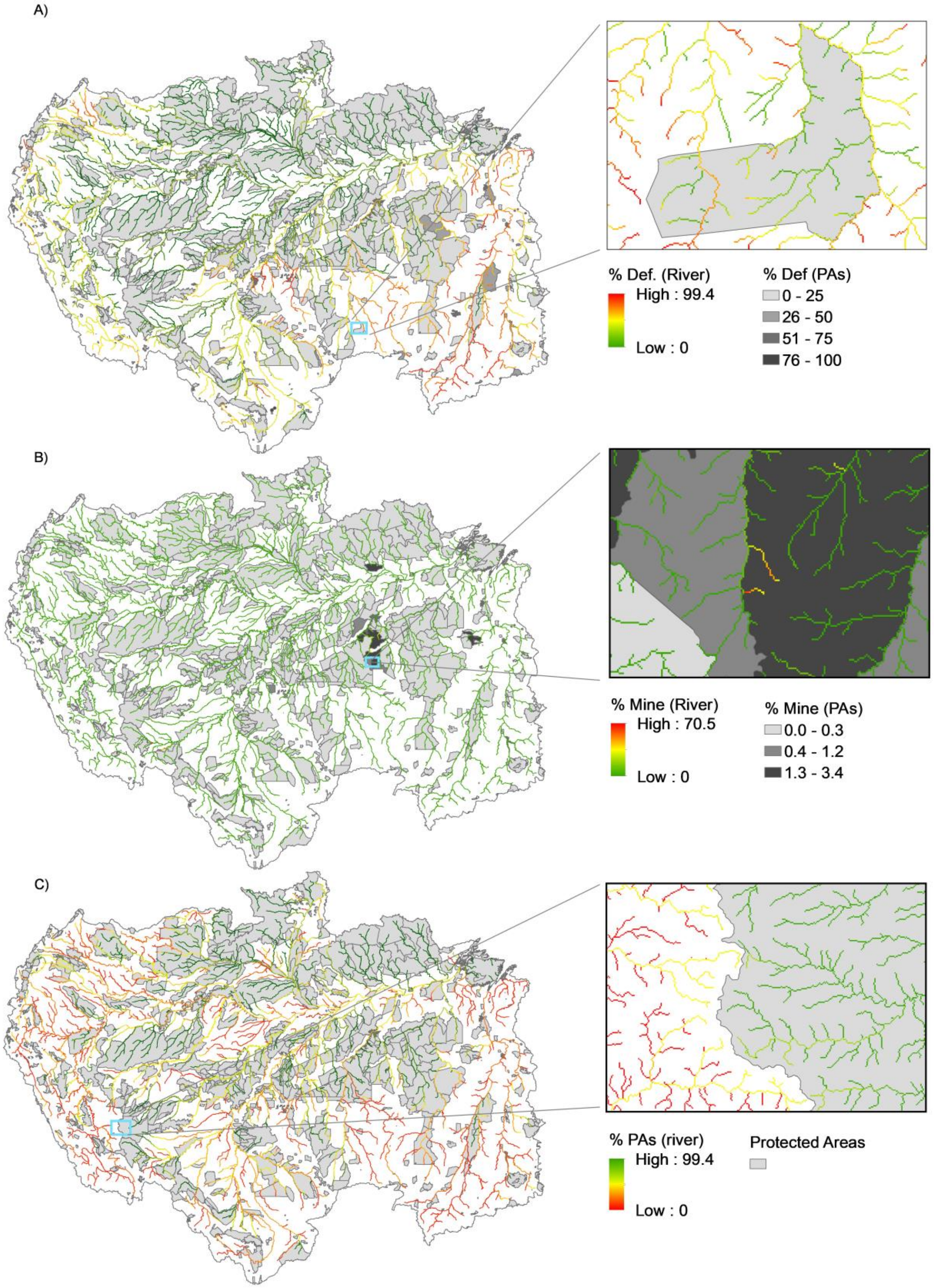
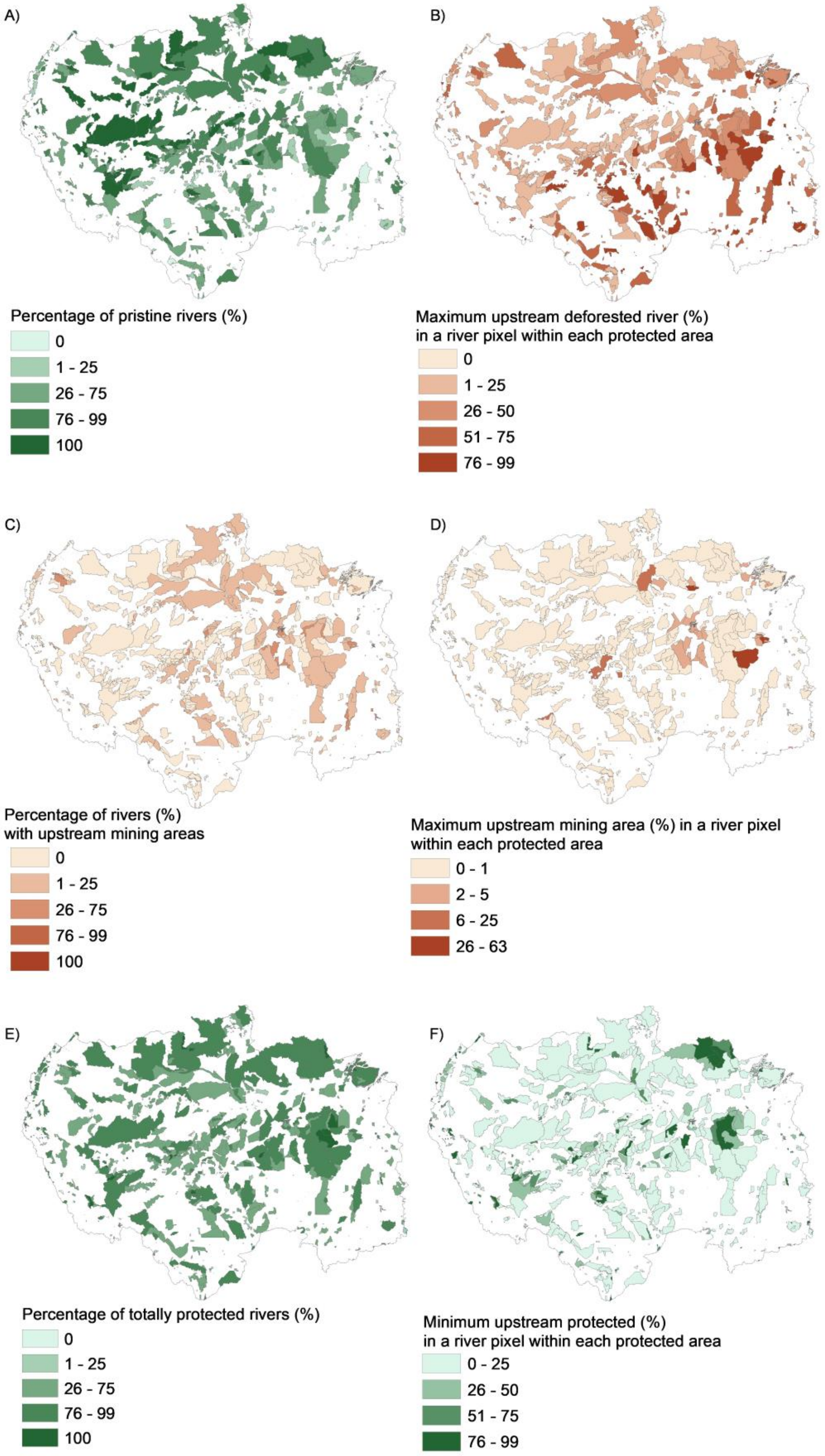

A)
% Def. (River)
High : 99.4
Low : 0
% Def (PAs)
0 - 25
26 - 50
51 - 75
76 - 100
B)
% Mine (River)
High : 70.5
Low : 0
% Mine (PAs)
0.0 - 0.3
0.4 - 1.2
1.3 - 3.4
C)
% PAs (river)
High : 99.4
Low : 0
Protected Areas

Figure 6. Percentage of the river network within each Amazonian protected area classified as **a.** pristine (up to 1% deforestation upstream), **c.** with mining area upstream, and **e.** totally protected (more than or equal to 99% protection in its upstream area). The **b.** maximum percentage of upstream deforestation, **d.** upstream mining, and **f.** mining upstream protection are also shown. Due to overlaps, not all protected areas can be visualized.


A)
B)
Percentage of pristine rivers (%)
0
1 - 25
26 - 75
76 - 99
100
Maximum upstream deforested river (%)
in a river pixel within each protected area
0
1 - 25
26 - 50
51 - 75
76 - 99
C)
D)
Percentage of rivers (%)
with upstream mining areas
0
1 - 25
26 - 75
76 - 99
100
Maximum upstream mining area (%) in a river pixel
within each protected area
0 - 1
2 - 5
6 - 25
26 - 63
E)
F)
Percentage of totally protected rivers (%)
0
1 - 25
26 - 75
76 - 99
100
Minimum upstream protected (%)
in a river pixel within each protected area
0 - 25
26 - 50
51 - 75
76 - 99

Only 0.02% of the river network within the Amazon PAs has an upstream drainage area that is near total deforested, and 0.12% has an unprotected drainage area. In 14 PAs, there is at least one river pixel with a near total deforested (more than 90% of deforestation) drainage area, most of which are in the southern Amazon. Of these 14 PAs, 6 are IUCN category VI (PA with sustainable use of natural resources) and 5 are indigenous land. For example, in Mato Grosso state, the contiguous Paresi, Tirecatinga, and Utiariti indigenous lands (location indicated in the Figure 5a) have some near total deforested pixels inside. However, 63% of its river network is classified as totally protected, and no river pixel is unprotected. In this case, most pixels with high upstream deforestation rates occur in the rivers in the PAs' borders. Due to the low deforestation observed inside PAs, the accumulated deforestation commonly decreases as the river passes through a protected area, as observed for big rivers (Figure 5a) and the Itacaiúnas River basin (section 4.3). This attenuation effect highlights PAs' vital role in improving water resource conservation and the associated social-ecological systems.

In 5 small PAs (less than 24 km²), all river pixels analyzed were classified as unprotected. A more relevant case is the Jalapão Environmental Protected Area (IUCN category V), with about 1350 km²), where 36% of the river network is classified as unprotected.

There are upstream mining areas in 3.7% of the Amazonian river network inside designated PAs. This number reduces to 2.6% in the most restricted IUCN PAs categories (I to IV) and 2.6% in indigenous land, but reaches 6% in the IUCN categories V and VI. Although only 48 PAs contain some mining area, in 234 PAs, there is at least one river pixel with some mining area upstream (Figure 6d). In 10 small PAs, including four indigenous lands, all mapped river network have mining areas upstream. However, they do not contain any mining areas inside them. An impressive case is provided by the Environmental Protected Area of Tapajós (IUCN category V, located in the Brazilian State of Pará) (Figure 3b), which has a relatively large area (20,537 km²), and 81% of its river network is affected by mining in its upstream area. The maximum percentage of mining area in the drainage area of a river pixel observed in this PA was 20%. It is the third PA with more mining area inside it (1.7%). The maximum values per river pixel in PAs occur in two Conservation Units located in the Itacaiúnas River basin (section 4.3): the Carajás National Forest (up to 63%) and Igarapé Gelado Environmental Protection Area (up to 42%). These high rates of mining activity are due to industrial mining activities within them (Figure 6d).

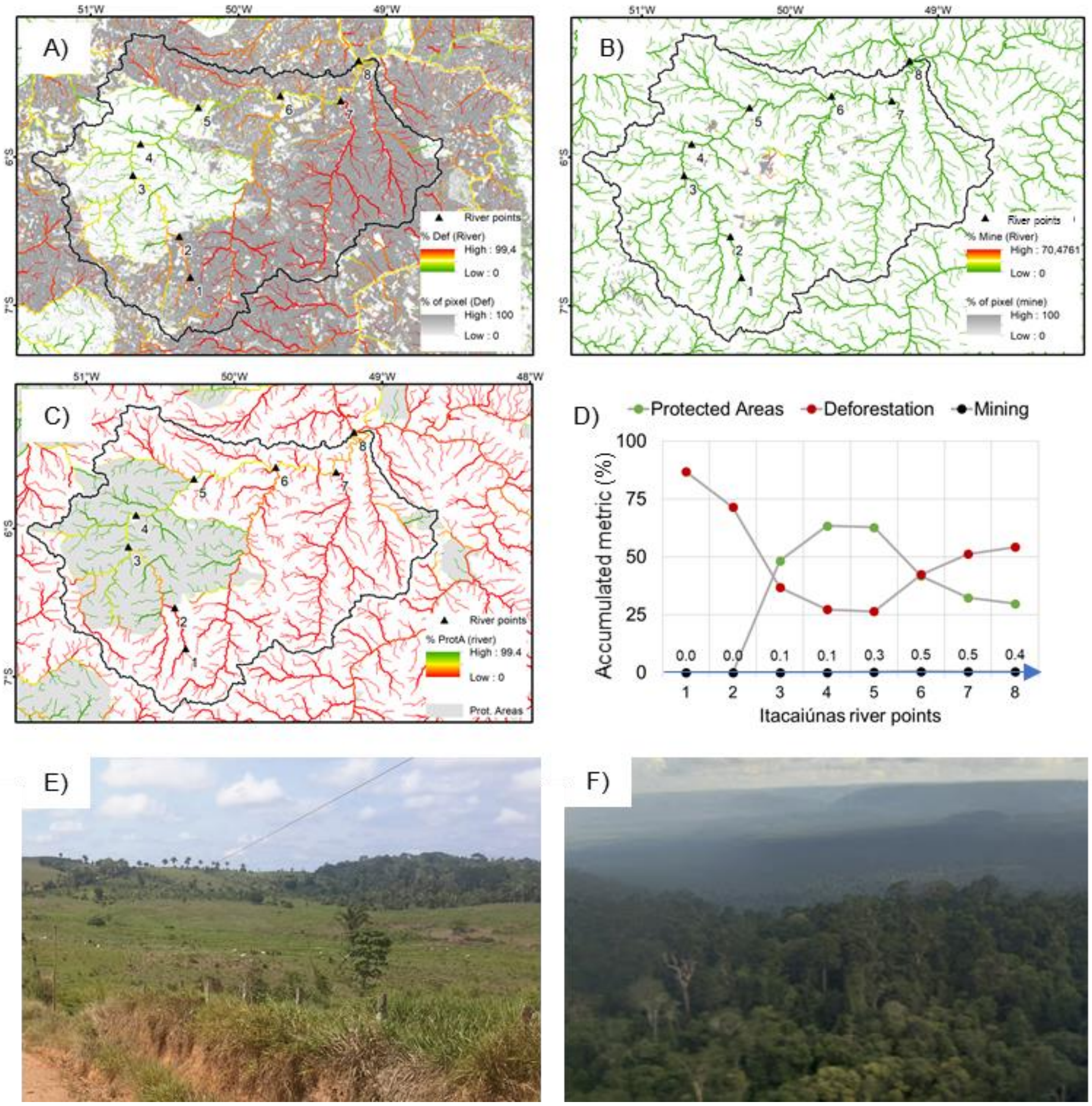
4.3 Study case: Itacaiúnas River Basin

The Itacaiúnas River basin is the Amazon subbasin, with the highest percentage (14%) of its river network classified as near total deforested. It also contains the river pixel inside a PA with the highest rate of upstream mining areas (63%). Approximately one-quarter of the basin is protected (conservation units and indigenous land), primarily located in a contiguous area in the western part of the basin and covered by primary forests (Figure 7f).

The Itacaiúnas River enters the mosaic of PAs with 0% of its 863 km² drainage area protected, 74% deforested, and 0% mined (point 2 in Figure 7). Within these PAs, only 4% is deforested, and 0.78% is associated with industrial mining activities, which are included in its management plan. After traveling 180 km within the mosaic of PAs and receiving several tributaries, it leaves the mosaic with a drainage area of 13,029 km², of which 63% is protected, 25% is deforested, and 0.3% is associated with mining (point 5).

Approximately 75% of the non-protected areas are deforested, most of which was converted to pasture (Figure 7e). The Sororó River basin, the eastern main Itacaiúnas tributary, has almost half (46%) of its river network with upstream near total deforested area. After receiving this tributary, the Itacaiúnas River reaches its mouth with a deforestation level of 51% in its drainage area (point 8).

Figure 7. a. Deforestation and percentage of upstream deforested areas in the Itacaiúnas River basin. The same is presented for **b.** mining and **c.** protected areas. **d.** Profile of upstream accumulated land use for eight points (upstream-downstream direction) along the Itacaiúnas River. Illustrative photos of **e.** a forested area converted into pasture and **f.** a forest area within a protected area are also presented.



5 Discussion

5.1 Implications for environmental management along the Amazon River basin

We showed that almost half of the Amazonian river network has unprotected drainage areas, only one-third can be considered pristine (less than 1% deforestation upstream), and 5% have some upstream mining areas. Approximately one-third of the Amazonian river network has deforestation levels of more than 20% in their upstream areas, concentrated in the east and south of the basin. This figure is remarkable because 80% of the area of each rural property in the Brazilian Amazon must be covered with native vegetation (Federal Law 12651/2012). Areas surrounding springs and headwater watercourses, in addition to other permanent preservation areas, should also be preserved. However, a portion of these areas do not need to be restored, and there is much illegal deforestation. Therefore, enforcing the restoration of these areas within private rural properties can decrease the accumulated upstream deforestation in the Amazonian rivers.

The threshold of 20% deforestation in the drainage area is also interesting given that many classical studies suggest it as the threshold beyond which one can measure direct impacts on streamflow (Bosch & Hewlett, 1982; Stednick, 1996). Therefore, deforestation is expected to affect streamflows in one-third of Amazonian river networks. Variations in the natural flow regime can impact not only aquatic but also the terrestrial biodiversity since rivers, wetlands and floodplains can represent barriers or opportunities for species dispersal (Brauer et al., 2013; Paquette et al., 2006; Wishart, 2000). Since we included only rivers with a drainage area greater than 20 km² in our analysis, worse results could be expected in unmapped smaller rivers.

5.2 Protection of rivers within protected areas

Rivers cross geopolitical boundaries. The need for multicountry cooperation has been stressed by several studies, e.g., for reducing dam impacts across the basin (Flecker et al., 2022) and mitigating water stress (H. A. Munia et al., 2020). The same need is observed to define protected areas to conserve fluvial ecosystems toward a basin-wide conservation framework (Castello et al., 2013; Reis et al., 2019). According to the Brazilian National System of Nature Conservation Units, creating and managing conservation units must guarantee the integration of surrounding land and water. This statement is in accordance with the river catchment concept. However, although PAs in Brazil have proven effective in curbing deforestation, and part of the protection is partially extended to the buffer zone (Barros et al., 2022; Gonçalves-Souza et al., 2021), their effectiveness in conserving freshwater ecosystem biodiversity is expected to be lower.

As seen in the case of the Itacaiúnas River basin, a PA that has been effectively protected against deforestation may have upstream areas with high deforestation rates, because its boundaries do not respect the catchment limits, which can threaten freshwater biodiversity. Land cover changes in the headwaters of the Itacaiúnas River, outside PAs, caused statistically significant changes in discharges propagated within the PAs rivers, but the changes were reduced throughout the PAs due to the conservation status of these areas (Pontes et al., 2019). Between 10% and 20% of the deforested area of the basin must be restored for compliance with Brazilian environmental legislation, which could mitigate some of these effects (Nunes et al., 2019). Additionally, recent and uncontrolled artisanal mining activities have impacted basin-wide surface water quality (Salomão et al., 2023).

In addition to creating new areas and changing the limits of existing areas, an alternative in Brazil is the inclusion of unprotected areas upstream of rivers within protected areas that are a priority for protection as part of the buffer zone of protected areas. Thus, despite remaining unprotected, the management plan for protected areas would indicate that activities could be developed in the region so as not to affect the protection of biodiversity,Of greatest concern are the rivers with near total deforested drainage areas, or with upstream mining, that enter indigenous lands. This situation can lead to unsafe drinking water, impaired fishing, and other impacts to vulnerable people with limited access to basic sanitation and with an already high rate of water-related diseases (Escobar et al., 2015; Jiménez et al., 2014). In Brazil, the Hydrographic Basin Committees whose territories include indigenous lands must include representatives of the National Foundation of Indigenous Peoples and indigenous communities residing or with interests in the river basin. However, the inclusion process is limited and indigenous people can need specific training to reduce the barriers to their effective participation in water management (Galvão, 2013).

5.3 Using upstream accumulated landscape metrics to manage freshwater ecosystems

One of the targets of the Kunming-Montreal Global Biodiversity Framework is to ensure that by 2030 "at least 30% of terrestrial, inland water, and of coastal and marine areas are effectively conserved and managed through ecologically representative, well-connected and equitably governed systems of protected areas." For global freshwater biodiversity, which is under a steep decline (Acreman et al., 2019), this requires considering the connectivity of the rivers and the watershed landscape. This target also requires studies that analyze the effectiveness of PAs to protect rivers and not just avoid deforestation within them.

The upstream accumulated landscape metrics can be integrated with other datasets, such as those on water quantity and quality, and social and freshwater biodiversity, to provide a more comprehensive understanding of the drivers and impacts of deforestation, mining, and protection on ecosystem services linked to Amazonian aquatic habitats and the people that rely on it. As we used datasets that are regularly updated (Mapbiomas and IUCN), it is possible to monitor changes in the accumulated land use over time, which can help to identify hotspots that require immediate conservation measures. Such information is important to indicate priority areas to restore, aiming at protecting river ecosystems. This could be achieved by creating freshwater protected areas or revising protected areas to address both terrestrial and aquatic ecosystems, as previously suggested (Leal et al., 2020; Saunders et al., 2002). In the Brazilian Amazon, 50 Mha is non-designated public forests (Azevedo-Ramos et al., 2020), and future studies should analyze their potential to help protect the headwaters of strategic rivers, such as those that flow within indigenous lands, and freshwater biodiversity hotspots.

6 Conclusions

The impacts of human activities and land management on rivers may go unnoticed if we do not consider what occurs in their entire drainage area. Although this concept is rather intuitive, conservation measures in the Amazon Basin have seldom considered it in their protection framework. The generated accumulated land use (deforestation and mining areas) for each 15-arc pixel of a Amazonian river network can provide important insights into the actual conservation status of rivers. Here we showed that almost half of the Amazonian rivers has unprotected drainage areas, only one-third can be considered pristine (less than 1% deforestation upstream), and 5% have some upstream mining areas. With this approach, hotspots can be identified and used for prioritizing conservation efforts or targeting interventions to reduce deforestation or improve protection in high-risk areas.

Almost half of the rivers in protected areas are, in truth, unprotected because the delimitation of the protected area does not cover its upstream drainage areas, which can threaten freshwater biodiversity. Such information is also fundamental to indicate priority areas to restore, aiming at protecting river ecosystems within the already existing protected areas and the services they provide.

Data availability

Hydrosheds drainage direction data are available at https://developers.google.com/earth-engine/datasets/catalog/WWF_HydroSHEDS_15DIR. The MapBiomas data are available from https://mapbiomas.org/. The PAs are available from at https://developers.google.com/earth-engine/datasets/catalog/WCMC_WDPA_current_polygons#description. The upstream deforestation, mining, and protection for the river network and by AP and sub-basin have been uploaded to Figshare, link: https://figshare.com/articles/dataset/MapRios/23261450.

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