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Damming the rivers of the Amazon basin

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More than a hundred hydropower dams have already been built in the Amazon basin and numerous proposals for further dam constructions are under consideration. The accumulated negative environmental effects of existing dams and proposed dams, if constructed, will trigger massive hydrophysical and biotic disturbances that will affect the Amazon basin's floodplains, estuary and sediment plume. We introduce a Dam Environmental Vulnerability Index to quantify the current and potential impacts of dams in the basin. The scale of foreseeable environmental degradation indicates the need for collective action among nations and states to avoid cumulative, far-reaching impacts. We suggest institutional innovations to assess and avoid the likely impoverishment of Amazon rivers.

Dams in the Amazon river basin have induced confrontations among developers, governmental officials, indigenous populations and environmentalists. Amazonian hydroelectric dams are usually justified on the basis that they supply the energy needed for economic development in a renewable form that also minimizes carbon emissions. Recent scientific reviews have considered the environmental impacts of damming Amazonian rivers[1–3], but regrettably, the effects of dams have been assessed mainly through studies undertaken only in the vicinity of each dam[4]. Such a local approach generally ignores the far larger, basin-scale, geomorphological, ecological and political dimensions that will determine the future productive and environmental condition of the river system as a whole. For networks of large dams on huge rivers[5], far less consideration has been given to the need to assess environmental impacts at regional to continental scales.

There is ample evidence that systems of large dams on trunk rivers and tributaries, constructed without anticipation of cumulative consequences, lead to large-scale degradation of floodplain and coastal environments[6–8]. In the Amazon, basin-wide assessments are complex and involve multiple countries and state institutions. Yet, because the social and environmental impacts of large dams are severe, disruptive and characteristically irreversible[9,10], there is a pressing need for assessment of the nature and exceptional international scale of their environmental impacts and for systematic consideration of their selection, design and operation in order to minimize these deleterious impacts. System-wide evaluation could also be used as a basis for examining trade-offs between energy production and other economic and socio-environmental values, and for anticipating and ameliorating unavoidable changes to economies, navigation, biodiversity and ecosystem services.

Here we provide an analysis of the current and expected environmental consequences that will occur at multiple scales if the proposed widespread construction of Amazonian dams goes forward. We move beyond qualitative statements and critiques by introducing new metrics—specifically a Dam Environmental Vulnerability Index or DEVI—to quantify the impacts of 140 constructed and under construction dams, and the potential impact of 428 built and planned dams (that produce more than 1 MW) in the Amazon basin. We find that the dams, even if only a fraction of those planned are built, will have important environmental consequences that are irreversible; there exists no imaginable restoration technology. These include massive hydrophysical and biotic disturbances of the Amazon floodplain, estuary, and its marine sediment plume, the northeast coast of South America, and regional climate. However, the extent and intensity of impacts on specific biological groups are uncertain and need to be explored during future work.

We assessed the current and potential vulnerabilities of different regions of the Amazon basin and highlight the need for a more efficient and integrative legal framework involving all nine countries of the basin in an anticipatory assessment of how the negative socio-environmental and biotic impacts of hydropower development can be minimized to achieve environmental benefits for the relevant riverine communities and nations.

Amazonian rivers and dams

The Amazon river system and its watershed of 6,100,000 km^2 comprise Earth's most complex and largest network of river channels, and a diversity of wetlands that is exceptional in both biodiversity and in primary and secondary productivity[11]. The river basin discharges approximately 16% to 18% of the planet's freshwater flow to its large estuary and the nearshore Atlantic Ocean[12,13]. Four of the world's ten largest rivers are in the Amazon basin (the Amazon, Negro, Madeira and Japurá rivers), and 20 of the 34 largest tropical rivers are Amazonian tributaries[14]. The Amazon is also the largest and most complex river system that transfers sediments and solutes across continental distances, constructing and sustaining Earth's largest continuous belt of floodplain and a mosaic of wetlands encompassing more than 1,000,000 km^2.

The sediment regimes and geochemistry of Amazon tributaries differ according to the dominant geotectonic regions that they drain[15]. Andean mountains and Andean foreland rivers are rich in suspended sediment and solute loads, and the water pH is near neutral. Cratonic rivers are characterized by low suspended sediment load and low pH, and are often highly enriched in dissolved and particulate organic carbon. Lowland rivers drain sedimentary rocks and transport an abundant suspended sediment load entirely within the tropical rainforest. A fourth mixed-terrain category including Andean mountains, foreland and cratonic areas applies only to the Madeira basin because of the complexity of its geotectonic domains.

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The fluvial channels and floodplain morphologies, the amount and characteristics of the sediments transported by the rivers, the annual flood pulse, and the action of morphodynamic erosional–depositional processes in space and time provide disturbance regimes that result in high habitat diversity of the alluvial landscape, high biotic diversity, and high levels of endemism for both aquatic and non-aquatic organisms[16,17].

We identified 76 existing dams or dams under construction on the cratonic rivers of the Amazon basin, 62 in the Andes, and two dams in the foreland–cratonic transition, in the Madeira river. Planned installations include 136, 146 and 6 dams in the Andean, cratonic and lowland environments respectively. The proposed dams include small, large and mega projects that account for 48%, 45% and 7% of the total number respectively (see Fig. 1 and its Source Data). Three of the ten largest mega dams in terms of power generation are built or near completion: the Belo Monte (11,233 MW) dam on the Xingu river; and the Santo Antônio (3,150 MW) and Jirau (3,750 MW) dams on the Madeira river. The remaining seven largest are still in planning stages, underlining the need for immediate attention to the impacts of these mega construction projects. The only planned Andean storage mega dam in the top ten is on the Marañon (4,500 MW) river in Peru, but many others have been proposed for the sediment-rich Andean source regions (Fig. 1).

Dam Environmental Vulnerability Index

Here we present a Dam Environmental Vulnerability Index (DEVI) and undertake a large-scale assessment of the environmental impact of existing, and planned Amazonian dams. This allows us to provide vulnerability maps for the 19 major Amazon sub-basins by considering two scenarios: existing and under-construction dams in 2017 (Supplementary Fig. 2), and all dams, whether existing, under construction or planned (Fig. 2).

The DEVI is a measure of the vulnerability of a basin's mainstem river resulting from existing and potential conditions within the basin and combines the following three sub-indices (Supplementary Information). DEVI is also a useful tool to compare the potential hydrophysical impacts of proposed dams on the fluvial systems with the spatial distribution of biological diversity. (i) the Basin Integrity Index (BII), which quantifies the vulnerability of the river basin to existing and potential land use change, potential erosion and runoff pollution; (ii) the Fluvial Dynamics Index (FDI), which gauges the influence of fluxes of sediment transported by the rivers, the morphodynamic activity of the rivers, and the stage-range of the flood pulse; (iii) the Dam Impact Index (DII), which quantifies how much of the river system will be affected by the planned and built dams.

DEVI values range from 0 to 100, with higher values indicating greater vulnerability of a sub-basin. The contribution of each individual index to the basin vulnerability is also examined (Fig. 2, Supplementary Figs 2 and 3, and Supplementary Table 1).

Andean foreland sub-basins

The Andean Cordillera (approximately 12% of the Amazon basin area) provides more than 90% of the detrital sediment to the entire system[12,18], out of which wetlands are constructed, and supplies most of the dissolved solids and nutrients transported by the mainstem Amazon river to its floodplains, estuary and coastal region[19] (Fig. 1). The sediment yields of the Andean tributaries are among the highest on Earth, comparable to basins in the Himalaya and insular Southeast Asia[20].

Of the five major Andean sub-catchments, three account for most of the planned, constructed and under-construction dams in this region: the Ucayali (47 dams), Marañon (104 dams) and Napo (21 dams) catchments (Fig. 1). The dams are located in areas of high sediment yield, at an average elevation of 1,500 m (Fig. 1). The upper Napo river basin in Ecuador underwent accelerated construction of dams in recent years and currently exhibits moderate DEVI values (Supplementary Fig. 3). However, when assessing the potential impact of planned dams, the most vulnerable rivers will be the Marañon and Ucayali, with DEVI values of 72 and 61 respectively (Fig. 2). An additional environmental concern is that these threatened fluvial basins harbour a large diversity of birds, fish and trees[21,22]. Their BII values range from high to moderate. In general, the anthropogenic and cover of these watersheds is large (>29%) and the amount of protected area upstream from the lowermost planned dam is relatively small (20–32%). High values of FDI are mainly related to

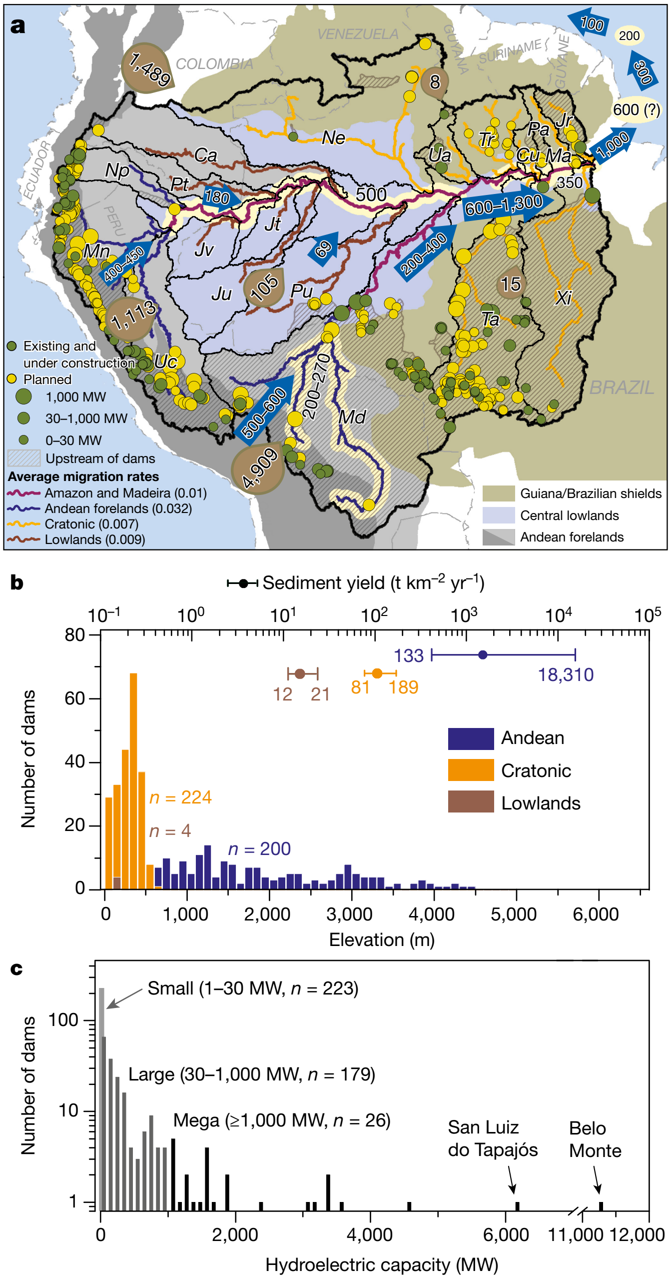

Figure 1 | The Amazon's 19 sub-basins: geologic–physiographic domains, sediment fluxes, channel migration rates and dams. a, The Andean foreland rivers are: Marañon (Mn), Ucayali (Uc), Napo (Np), Putumayo (Pt) and Caqueta-Japura (Ca). The cratonic rivers are: Jari (Jr), Paru (Pa), Curuapenema (Cu), Maricuru (Ma), Tapajós (Ta), Xingu (Xi), Trombetas (Tr), Negro (Ne) and Uatumã (Ua). The mixed-terrain river is: Madeira (Md). The lowland rivers are: Juruá (Ju), Purús (Pu), Jutaí (Jt) and Javari (Jv). Averaged sediment yield (t km^{-2} yr^{-1}) for major sediment source terrains is shown as brown 'balloons'[12,20]; sediment loads (Mt yr^{-1}) are shown as blue arrows; major depositional zones (storage, Mt yr^{-1}) are shown as yellow shading[12,18]; and mean channel migration rates (channel widths per year) are shown by physiographic province[23] (red, green and blue lines). Migration rates of 0.01 were estimated for the Solimões–Amazon and Madeira rivers (purple line). **b**, Numbers of dams in each elevation range (bars) and geological region (Andean mountains, cratonic and lowlands). Ranges and means of sediment yields (t km^{-2} yr^{-1}) measured in each region are shown along the upper x axis. **c**, Histogram of the number of dams scaled by their hydroelectric capacity.

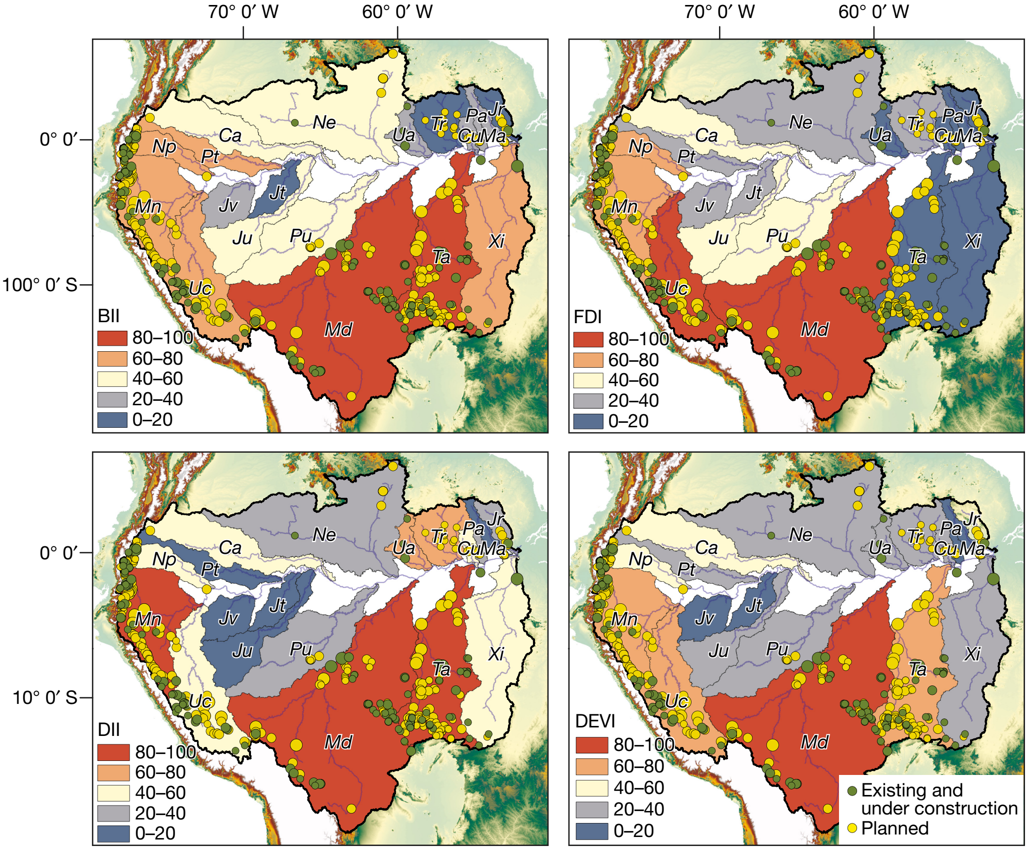

Figure 2 | Vulnerability indices of sub-basins in the Amazon for existing, under construction, and planned dams. The Basin Integrity Index (BII), the Fluvial Dynamics Index (FDI), the Dam Impact Index (DII), and the combined Dam Environmental Vulnerability Index (DEVI). Red colours indicate highest vulnerability based on the three indices; blue basins are least vulnerable. Dots indicate dam locations.

high sediment yields, high channel migration rates (about 0.046 channel widths per year) and moderate to high water stage variability. High rates of channel cutoff and abandonment result in oxbow lakes and atrophied branches, leading to increased sediment storage. The Ucayali is the most sensitive river in this regard (Fig. 1). The Marañon river is critically threatened and its DII is very high because it would be affected by a large number of dams concentrating along most of the mountainous course of the main channel (Figs 1 and 2).

Cratonic sub-basins

The ten cratonic sub-basins (Fig. 1) host rivers that drain moderate- or low-elevation Precambrian shields and old sedimentary and basaltic plateaus, and have low sediment yields, very low migration rates (about 0.008 channel widths yr^{-1})[23], and moderate annual variability of mean water stage (water stage variability), resulting in low FDI values (Figs 1 and 2).

Despite the fact that the mainstem of the Tapajós has not yet been disrupted by dams, this basin exhibits the largest values of DEVI among cratonic basins owing to the recent proliferation of constructed and under-construction dams on the major tributaries (Supplementary Fig. 2). The Xingu river was recently affected by the construction of the Belo Monte megadam (Supplementary Fig. 2). When assessing the impact of planned dams, the Tapajós is also the most threatened cratonic river, followed by the Xingu, Trombetas and Uatumã rivers ($\text{DEVI} < 35$) (Fig. 2). The BII value is higher in the Tapajós sub-basin (87) than in the Xingu basin (63), because the Tapajós has less protected area upstream of the lowermost dam and a larger deforestation rate. Anthropogenic land cover is large in both basins (around 61% and 48%, respectively) and anthropogenic disturbance of the landscapes, enabled by the scarcity of protected areas in southeastern cratonic basins, has begun to increase sediment supplies[24] (Supplementary Fig. 3).

The Tapajós river will suffer much higher hydrophysical and ecological impacts than will the Xingu river because of the far larger number of planned dams distributed along hundreds of kilometres of the river. With all planned (90) and existing (28) dams in place, the Tapajós river itself and all its major tributaries will be impounded. Together with the Madeira and Marañon, the Tapajós sub-basin is one of the most threatened in the Amazon basin (Fig. 2 and Supplementary Figs 2 and 3). Despite limited knowledge about the biodiversity of this basin, the information available in environmental studies required by law to assess the impact of planned dams[25,26] indicates that the Tapajós river harbours unique fish and bird species that are considered to be threatened by existing and planned dams, and some of the fish species are officially included in the Brazilian Ministry of the Environment List of species at risk of extinction (Supplementary Table 2). Coincidentally, our DEVI assessments point that the Tapajós river needs to be a priority area for further detailed studies regarding impacts of dams on aquatic ecosystems and biodiversity.

Some smaller cratonic sub-basins such as the Jari (1 constructed, 4 planned dams) and Paru (3 planned dams), have relatively low DEVI values around 11, as a result of being well protected and having fewer planned dams (Fig. 2, Supplementary Fig. 3).

Lowland sub-basins

The lowland rivers drain Tertiary sedimentary rocks that remain mostly covered by rainforest. Because of their low gradients and lack of rapids, these rivers are free of dams. The six dams planned for the Purús river are not on the main channel, and for that reason its DEVI value (34) is only moderate (Fig. 2). Anthropogenic land cover disturbance in these sub-basins is also relatively low: Purús (24%), Juruá (28%), Jutaí (12%) and Javari (18%). However, the BII values of the Purús and Juruá sub-basins are 40 and 44 respectively (Fig. 2).

Madeira sub-basin

The Madeira river, the largest Amazon tributary in terms of drainage area, water and sediment discharge, has been strongly affected by the recent

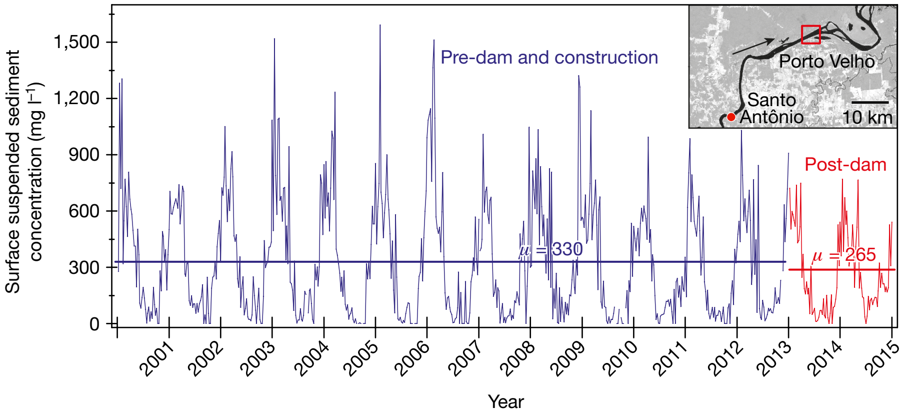

Figure 3 | Changes in surface suspended sediment concentration in the Madeira river downstream of the Santo Antônio dam (8° 48′ 06″ S, 63° 57′ 03″ W) for pre-and post-dam construction periods. Horizontal coloured lines indicate mean surface suspended sediment concentrations μ for each period: pre-dam construction (2001–2013), and post-dam construction (2014–2015). A decrease of 20% in the mean annual surface suspended sediment concentration is detected in the Madeira river (details of methods are available in Supplementary Information section 2). The red rectangle in the inset indicates the area used for the Moderate Resolution Imaging Spectroradiometer-Surface Suspended Sediment Concentration (MODIS-SSSC) calibration; Porto Velho is a city in Rondonia, Brazil.

construction of dams and currently exhibits the largest values of DEVI of the whole Amazon basin (Supplementary Fig. 2).

However, the future environmental perspective is even worse. With 83 dams planned or built, 25 on Andean tributaries, 56 on cratonic tributaries, and two on the mainstem, the sub-basin of the Madeira river is also the most threatened in the Amazon (DEVI > 80) (Figs 1 and 2). Nearly 80% of the Madeira river watershed, an area with high sediment yield, lies upstream of the Madeira River Hydroelectric Complex, which consists of two recently constructed mega-dams (the Santo Antônio and Jirau dams) and two dams planned at the Bolivian–Brazilian border and within Bolivia. The large potential impact to the Madeira sub-basin indicated by the DEVI is especially alarming as this sub-basin harbours high biological diversity associated with its fluvial habitats[21,22].

The Madeira river's FDI is characterized by low channel migration rates, high water stage variability (12–14 m) and high sediment yield. Cratonic tributaries generate about 36% of the Madeira river discharge and have lower values of FDI (owing to lower sediment load, water stage variability and migration rates) than the Andean foreland tributaries but high DII values because of the lengths and flooded areas of the impoundments. The dams planned for the Andean foreland would affect major rivers (the Madre de Dios, Beni and Mamore rivers) that have the highest sediment yields of the entire Andes–Amazon watershed (Fig. 1). The channel migration rates in these foreland rivers are very high, and the Beni and Mamore floodplains store about 280 Mt yr^{-1} of sediment on the Bolivian plains[27] while their water stage variability is moderate (Fig. 1).

The Madeira river accounts for approximately 50% of the total sediment transported into the Amazon river system from Bolivia and Peru, and sediment trapping by its large dams will be a major problem. Although assessments of sediment transport and trapping conducted by governmental and independent consultants are controversial[28], it is estimated that about 97% of the sandy load would be trapped upstream of the Santo Antônio and Jirau dams[29]. These estimates do not account for the trapping effects of the 25 upstream storage dams planned for the Andean reaches and upstream lowlands and palliative flushing strategies that may be implemented. Using satellite-based observations (Supplementary Text 2), we estimate the surface suspended sediment concentration, immediately downstream of the Santo Antônio dam for the years 2001–2015. Our results indicate that the Santo Antônio and Jirau dams caused an approximately 20% decrease in the mean surface suspended sediment concentration of the Madeira river (Fig. 3), despite unusually high flood discharges in 2014 and 2015.

Mainstem Amazon system and Amazon sediment plume

The Amazon river mainstem sustains a biologically rich floodplain with an area greater than 100,000 km^2 (ref. 30). Despite the high sediment yields of its Andean catchments, the Amazon basin sediment yield at the continental scale is only moderate (about 216–166 Mt km^{-2}) because much of its sediment supply is stored in its floodplains. For 2,000 km along the Brazilian Amazon river, exchange of sediment between the channel and the floodplain exceeds the annual flux of sediment (about 800–1,200 Mt yr^{-1}) discharged from the river at Óbidos, the farthest-downstream measuring station[12,18]. The processes of channel–floodplain exchange include bank erosion, bar deposition, particle settling from diffuse overbank flow, and sedimentation in floodplain channels, levees and internal deltas, and are associated with a mean channel migration rate of 0.02% ± 20% channel widths per year and a water stage variability[18,31] of about 10 m (Fig. 1). Sediment storage along the whole Amazon river (channel–floodplain system) from the Peruvian border to Óbidos is approximately 500 Mt yr^{-1} (Fig. 1). The lower Amazon river between Manacapuru and Óbidos, with its large fluvial lakes and wetlands, is a particularly crucial and vulnerable area from an ecological and geomorphological perspective. An estimated 162–193 Mt yr^{-1} of sediment is stored in the floodplain along this reach of the Amazon river[12]. An additional estimated 300–400 Mt yr^{-1} of sediment is deposited in the lower fluvial reach and delta plain[18] (Fig. 1). The implied decrease of sediment along the main channel and floodplains of the mainstem Amazon will have major impacts on its sediment dynamics and ecology.

A recent vulnerability assessment suggested that the Amazon mouth is at "low to moderate risk" when compared to other deltas of the world[32]. However, these assessments in deltas are typically focused on land loss, and the mouth of the Amazon has more characteristics of an estuary than of a delta. The assessment in ref. 32 of the Amazon mouth probably underestimates the cumulative effects of dams and the impacts on the environmental functions and services provided by the lower Amazon and its plume because the assessment does not appear to consider the current effects of very recently constructed dams nor the future effects of those dams that are under construction and planned.

The role of Amazon sediments on coastal and marine ecosystem functions is not fully understood. About 200–300 Mt yr^{-1} of muddy Amazon sediment is transported northwestward along the Atlantic continental shelf towards the Guyana and Venezuela coast[33]. These sediments provide substrate and nutrients for the largest preserved mangrove region of South America, which spans Marajo Island, the coastline of the Pará and Amapá states of Brazil, and the Guianas. Another recent discovery confirmed the existence of an extensive carbonate reef system of around 9,500 km^2 from the French Guiana border to the state of Maranhão in Brazil (about 1,000 km); this reef system has unique functions owing to the influence of the plume, which provides ecosystem services and acts as a selective biogeographic corridor between the Caribbean and the southern Atlantic Ocean[34]. Our understanding of the environmental links and mechanisms

BOX 1

The Amazon Cooperation Treaty (ACT), signed by Brazil, Bolivia, Colombia, Guyana, Ecuador, Peru, Venezuela and Suriname, aims to promote the sustainable development of these Amazon countries. It is the legal instrument that recognizes the transboundary character of the Amazon river basin. Its executive arm is the Amazon Cooperation Treaty Organization (ACTO). The countries of the Amazon basin (except Guyana) are also signatories of the Ramsar Convention (http://www.ramsar.org/), which stipulates the sustainable use of wetland resources, rivers and other continental wetlands.

Of the ACTO members, Brazil leads regarding water policies and legislation. Brazil's main legal framework for this is the Brazilian Water Management Act (Law 9433/1997). The law sets standards for a decentralized and participatory water resources management system; considers river basins as the fundamental territorial units; defines strategies for water planning, management and governance; and contemplates the creation of river basin committees. These river basin committees, formed by representatives of the government sector, water users and civil society, are responsible for defining strategies for basin management, river basin planning and conflict mediation. The creation of a participative basin committee for the Amazon could follow the general lines of work and responsibility of the river basin committees.

Ongoing international basin management policies in the Amazon are nascent and concentrated in the MAP region—that is, the Madre de Dios, Acre and Pando departments, in Peru, Brazil and Bolivia, respectively. MAP aims to collaborate on the integrated management of the Acre river and it is the only international water initiative formed by civil society in the entire Amazon basin[45].

The main tool in Brazil and some Amazon countries for environmental governance and licensing is local environmental impact assessment, which in most cases does not provide adequate technical information for, and thus has had minimal influence on, policy decisions[58]. Additional tools such as strategic environmental assessments and integrated environmental assessments are being tried in Brazil, but the environmental impact assessment is still the only legal mandatory instrument for licensing. In Amazonian countries, the scale of assessment currently required for construction of dams is entirely local, and the decision-making process requires adequate analysis of hydrophysical and ecological impacts for the entire river system and coastal zone[59,60]. Improvements in the technical requirements of term of references, integrated assessment at the basin scale, and scrutiny of project viability by ACTO, and the proposed participative basin committee and Amazon Basin Panel, are required.

A proposal in Brazil to amend the federal constitution (PEC-65/2012-Brazilian Senate) will weaken environmental licensing for infrastructure projects by eliminating the current three-step process (preliminary, installation and operational) in favour of a simpler, but watered-down, environmental impact assessment[61,62].

Brazil modified its Forestry Code in 2012, facilitating legal deforestation of large portions of the Amazon floodplains[63]. Some legally protected areas were also degazetted or downsized to make room for planned and existing dams that overlap with conservation areas. These trends reverse the trend towards global environmental leadership shown by Brazil during recent decades. Change is needed to scale up cost–benefit analyses to encompass regional and transnational basinwide values.

of interactions between the Amazon plume and the coral reef is still rudimentary.

It has been suggested that the Amazon plume may also have interhemispheric climate effects, influencing precipitation in the Amazon forest as well as moisture convergence into Central America, the number and intensity of summer storms, and storm trajectories towards the Caribbean, Central America and the southern United States[35].

Sustainable solutions for Amazonian rivers

There is ongoing debate about the costs and benefits of building large dams: water development planners, engineers and economists have been shown to be overly optimistic and to systematically underestimate costs[36]. The costs of dams are much more difficult to estimate than those of other energy projects because each dam must be constructed to work within its particular environmental, geological and hydrological conditions[36]. Although large-scale hydropower is often seen as an attractive way to provide power to the Amazon region, economic uncertainties driven by climate change, land-use change and sensitivity to extreme drought events strongly affect projections of the economics of operation and power generation[37,38].

Recent research has shown that, even before taking into account negative impacts on human society and the environment, on average the actual construction costs of large dams tend to be too high to yield a positive financial return on investment[9,10,36,39]. Estimated benefits from water development are likely to be realized, but the unexpected environmental and social costs that typically occur with every dam project detract from the net benefits[40]. A global analysis of 245 large dams, including 26 major dams built between 1934 and 2007, demonstrated that actual costs averaged 96% (median 27%) higher than predicted, and one out of ten dams costs three times its estimate[36].

Furthermore, most of the dams, even those in Peru and Bolivia, are intended for exporting energy from their regions to cover Brazil's growing national demand for electricity, which was projected to increase about 2.2% annually up to 2050[41,42]. However, in the current economic situation the Brazilian government is reassessing this macroeconomic forecast and accepts that the middle-term growth rates of electricity demand are below previous estimates, that national plans for greater energy security overestimated the need for infrastructure, and that the demand by 2022 could be fully met with only 60% of the planned investments[43]. Thus, we suggest that the economic need and economic viability of dam construction in Brazil and the Andean countries need to be re-assessed. After the construction of three controversial mega-dams (the Belo Monte, Jirau and Santo Antônio dams), the Amazon countries have a second chance to reflect on the sustainable future of their unique fluvial resources.

We propose that it is essential for government agencies in all countries of the Amazon basin to formally recognize the gradually unfolding, but enormous, scale of dam-building impacts propagating through the riverine and coastal systems of the entire region, so that they can accurately assess, plan for, and avoid or ameliorate, the foreseeable degradation of the ecosystem services of these incomparable wetlands. Such recognition could provide a basis for trans-boundary communication and cooperation; a few examples are suggested here.

Current legislation only partially considers policies for national and international waters[44], and the licensing process to approve large infrastructure projects has been simplifed and weakened (Box 1). At the basin scale, it is critical to revitalize, improve and expand policy instruments such as the Amazon Cooperation Treaty Organization (ACTO), and to build new international actions based on existing legal instruments already available in Brazil but still inoperative in the Amazon, such as the Water Management Act (Law 9433/1997), which promotes an integrated water management system (Box 1).

ACTO could be the catalyst to build new international actions, policies and plans for river management. ACTO could also strengthen its technical and scientific capacity, consolidate existing programmes, and encourage more active participation of natural and social scientists engaged with stakeholders and decision makers. Such specialists could provide technical and scientific data by monitoring trends in sediment loads, the extent of wetland inundation, overbank flooding frequencies, coastal sediment plume size and riparian deforestation; they could anticipate environmental-socioeconomic impacts and suggest strategies for basin and resource management, as well as for avoidance of conflict.

We suggest that a legal transboundary water resources framework is required that has as its premise an integrative basin-scale approach. Proposals for the use of water resources by different agencies (energy, transportation and environment) must be combined into basin-scale, multi-faceted frameworks, rather than being isolated as independent competing entities. Social participation and basin-integrated management among states or department units of Peru, Brazil and Bolivia, such as the MAP collaboration for integrated management of the Acre river (a tributary of the Purús river) (Box 1), is an encouraging solution[45]. However, such regional plans need to be incorporated into a major decision-management tree at the basin scale and not simply atomized among a plethora of widely dispersed, independent, small projects in the basin.

A commission linked to ACTO, supported by an international panel of multidisciplinary experts (the Amazon Basin Panel), could produce assessments of the natural capital and its functioning, together with an assessment of socio-economic demands, conflicts and trends along the waterways of the Amazon river basin, and could define integrated and sustainable management plans for transboundary water resources. In this context, the assessment of vulnerability and impacts is a fundamental step. The DEVI measurement of vulnerability at sub-basin scales demonstrates that the recent construction of dams is profoundly affecting the Amazon basin, and predicts that, if the planned dams are constructed, their cumulative effects will increase the complexity and scale of the impacts. Our assessment also reveals why downstream nations and Brazilian states that are not directly involved in the construction of dams in their sovereign territories are nevertheless vulnerable to indirect environmental impacts and thus have reason to assess the consequences of dam building far upstream of their borders.

Amazon Basin Panel assessments could also provide the scientific basis for governments and society at all levels to develop policies that recognize the fundamental connectedness of river and coastal environments. We suggest participative strategies replicating the management of the Intergovernmental Panel on Climate Change (IPCC), involving members from ACTO countries, and additional members (such as France), and including scientists and international peer scrutiny. Like IPCC reports, the Amazon Basin Panel assessments could be policy-relevant but not policy-prescriptive. They may present projections of environmental impacts and issues based on different scenarios, and help suggest to policymakers a range of potential sustainable policies for river management.

The decision-making processes could be supported further through the creation of a participative basin committee of representatives of the different socio-political actors to discuss and define recommendations that consider socio-environmental governance and the protection of collective rights[46], under the coordination of ACTO (Box 1). Into that institutional context, a further policy instrument we suggest for reversing national–regional scale environmental degradation is the creation of new conservation units in the Amazon and hydro–socio-economic–ecological zoning regulations. These conservation units could be explicitly designed to recognize and protect watersheds, main channels, floodplains and eco-hydro-geomorphological services; and to assess sites of important natural, cultural, scenic and economic value to local communities.

Regarding energy policies, the medium-term demand for electricity can be met without sacrificing Amazon fluvial and coastal ecosystems and economies. One-off megaprojects—such as large dams, and large coal or nuclear plants—incur disproportionately large risks, which make them relatively unattractive compared to the more replicable alternatives[36,39,47]. Preliminary evidence suggests that modular solutions—including wind energy, solar energy, and on-site combined heat, cooling and power plants—provide compelling alternatives not only environmentally but also financially[48].

More flexible measures in Amazon countries could facilitate a smooth transition to a more diverse energy matrix based on other renewable sources in the mid- to long term, protecting the ecological services provided by the great, undammed Amazon rivers. Brazil, for example, has huge potential for the production of wind energy, (>143 GW), solar energy, and a variety of alternatives for hydropower besides large dams (such as small hydroelectric plants and river hydrokinetic energy)[49–52]. At present, Brazil is losing approximately 20% of the total energy produced within Brazil to deficient transmission[53]. Using a conservative projection, improvements in the transmission and distribution system and repowering and modernizing existing hydropower plants could increase energy delivery of approximately 2.84% (ref. 54). Peru also has a remarkable potential for wind, solar and geothermal energy but very little has been used[55,56].

In contrast to current policy, the energy sector needs to be a part of integrated Amazon-basin planning and management initiatives. At present, the energy sector tends to operate in the region as an independent agent imposed through vertical and centralized governmental decisions, but without a participative process that considers the needs and expectations of the local communities and that integrates the multidisciplinary scientific and technical information concerning the character and functioning of the Amazon river basin at multiple scales and locations, into political and socio-economic analyses. Scientists played a critical part in reducing deforestation in Brazil through monitoring systems, by assessing the role of forests in regional climate regulation, and by showing that agricultural production could be increased without further deforestation[57]. We propose that through the integration of available scientific knowledge, it will be possible to apply analogous strategies to the protection of natural resources in the Amazon fluvial and coastal systems.

Citizens of the Amazon basin countries will ultimately have to decide whether hydropower generation is worth the price of causing profound damage to the most diverse and productive river system in the world. If those decisions are made within the context of a comprehensive understanding of the fluvial system as a whole, the many benefits the rivers provide to humans and the environment could be retained.

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