RIVER ECOLOGY

Reducing adverse impacts of Amazon hydropower expansion

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Proposed hydropower dams at more than 350 sites throughout the Amazon require strategic evaluation of trade-offs between the numerous ecosystem services provided by Earth's largest and most biodiverse river basin. These services are spatially variable, hence collective impacts of newly built dams depend strongly on their configuration. We use multiobjective optimization to identify portfolios of sites that simultaneously minimize impacts on river flow, river connectivity, sediment transport, fish diversity, and greenhouse gas emissions while achieving energy production goals. We find that uncoordinated, dam-by-dam hydropower expansion has resulted in forgone ecosystem service benefits. Minimizing further damage from hydropower development requires considering diverse environmental impacts across the entire basin, as well as cooperation among Amazonian nations. Our findings offer a transferable model for the evaluation of hydropower expansion in transboundary basins.

Hydropower is a leading component of current and future renewable energy portfolios in many countries worldwide. Whereas the construction of new large hydropower projects has abated in much of Western Europe and North America (*1*), where coordinated dam removals are being considered (*2–4*), construction of large dams is booming in many countries with emerging economies (*5*, *6*). As plans for hydropower expansion ramp up for the world's few remaining unregulated and unfragmented river basins (*7*), tools for strategic dam planning are urgently needed to help minimize total environmental impacts at the basin scale, including transboundary river basins (*8*, *9*). Computational breakthroughs offer opportunities to guide dam site selection on the basis of trade-offs among many different criteria across multiple spatial scales and complex political landscapes (*10*).

From a socioenvironmental perspective, hydropower proliferation is an especially acute issue in tropical river basins such as the Amazon (*11–13*). Currently, at least 158 dams with individual installed capacities of >1 MW are operating or under construction in the five nations that constitute >90% of the Amazon basin, and another 351 dams are proposed (Fig. 1). The distribution of existing and potential hydropower is uneven among the major subbasins of the Amazon; most of the proposed sites are in either the Tapajós subbasin draining the Brazilian shield in the east (144 proposed dams) or the Marañón subbasin draining the Andes (62 proposed dams) (table S1). Relative to existing projects, many proposed Amazonian dams will be bigger and installed on larger rivers (Fig. 1B), leading to more-expansive river valley inundation and greater potential for socioenvironmental disruptions (*14*, *15*). Although integrated environmental assessments with site-specific environmental variables have been used in some Amazonian countries, particularly Brazil (*16*), these approaches rarely consider effects at the whole-basin scale, especially when rivers cross international boundaries. The variety of project sizes, combined with spatially heterogeneous river characteristics and transboundary resources, necessitates better understanding of the trade-offs between hydropower capacity and ecosystem services among different portfolios of future dams throughout the entire Amazon River network.

A multiobjective optimization framework

We developed a multiobjective optimization framework (*17*) to evaluate the trade-offs at large basin-wide scales between hydropower capacity and a set of five environmental criteria that encompass core river ecosystem services (or disservices)—river flow regulation, river connectivity, sediment transport, fish diversity, and greenhouse gas emissions—emerging from placement of dams across the entire river network. We constrained our analysis to these five environmental criteria because they could be estimated at each existing and proposed dam locality across the Amazon basin. These criteria also reflect fundamental riverine processes that underlie many benefits that ~30 million rural and urban people in the Amazon rely upon for their livelihoods, which are intimately linked to rivers and their floodplains. The natural flow regime of an undammed river fundamentally shapes riverine biodiversity and ecosystem function by mediating the timing and duration of sediment and dissolved nutrient transport,

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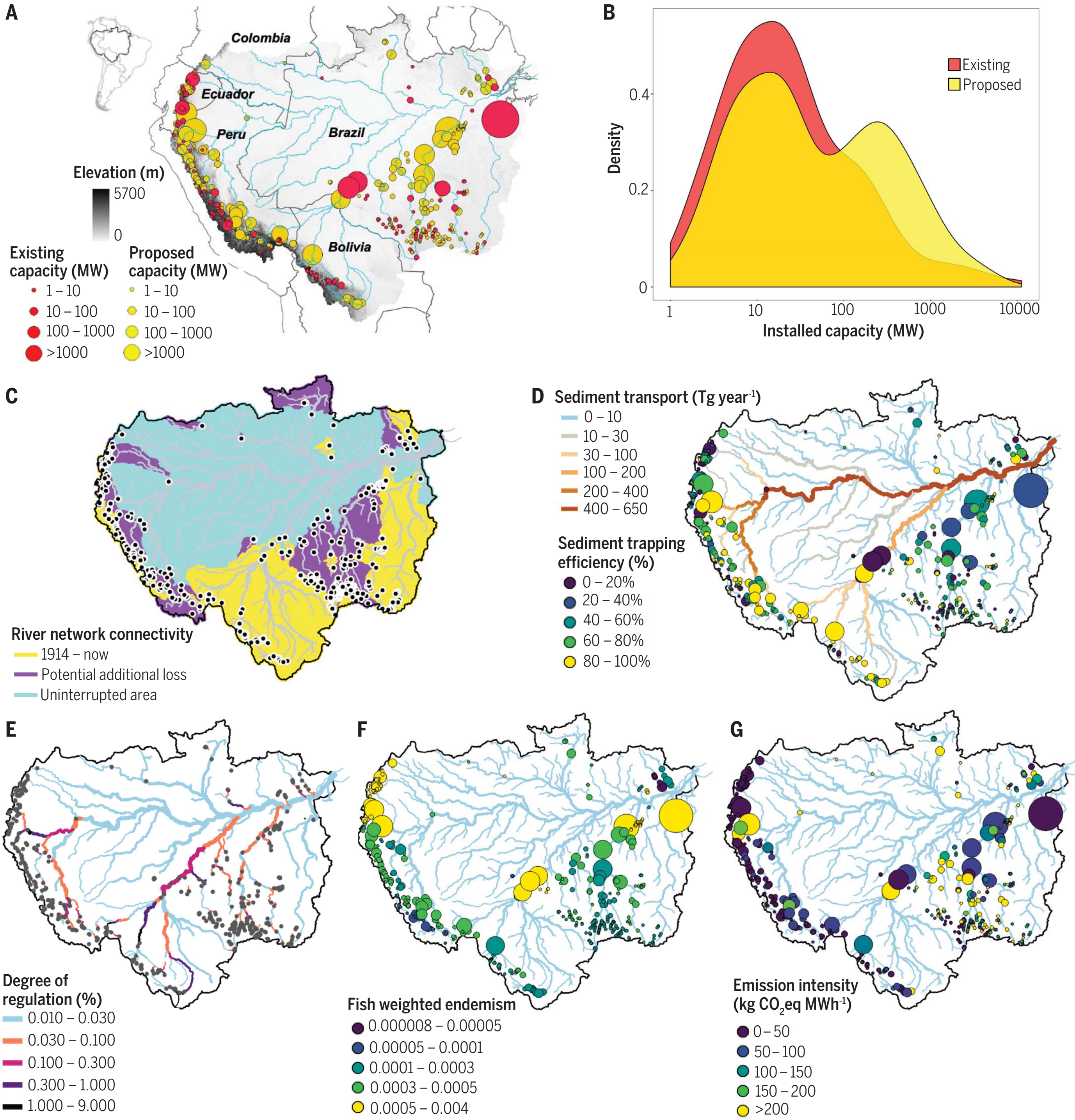

Fig. 1. Expansion of Amazon hydropower and comparative impacts for different environmental criteria. (**A**) Spatial distribution of 158 existing hydropower dams in the Amazon basin and 351 additional proposed dams. (**B**) Comparison of frequency distributions of existing and proposed dams as a function of installed capacity shows that dams are getting larger in the Amazon, with more projects proposed on large tributaries. The magnitude of impacts varies for different environmental criteria in different parts of the basin, as illustrated in the subsequent figure panels. (**C**) Existing dams have disconnected large fractions of the Amazon (yellow areas), as indicated by a river network connectivity index (RCI_D). Building all proposed dams would further disrupt Amazon basin connectivity (purple areas), with only about half of the basin remaining unfragmented (cyan areas). (**D**) Many dams with high sediment trapping efficiencies are proposed in sediment-rich river reaches in the western Amazon. (**E**) Cumulative degree of regulation, estimated as the percent annual flow that is withheld by upstream reservoirs with full buildout of all existing and proposed dams, can be manifested as alterations in the temporal dynamics of flow regimes and river-floodplain hydrological exchanges across the river network. (**F**) Some dams are located in subbasins that are fish diversity hotspots, as indicated by weighted endemism, which incorporates both fish species richness and endemism. (**G**) Estimated greenhouse gas emissions per unit of electricity generated at Amazon dams vary by more than two orders of magnitude. CO_2eq, carbon dioxide equivalent.

floodplain inundation, and habitat availability (*18*). Hydrologic connectivity of habitats via natural flows is vital for sustaining these riverine processes at river-basin scales (*7*). Dams interrupt these processes and associated ecosystem services by changing the magnitude and timing of water flux and can reduce the downstream delivery of suspended sediments. River sediments are critically important for building floodplains, which are nursery grounds of many food fishes and are used by people engaged in flood-recession agriculture (*19*, *20*). Moreover, river sediments carry nutrients essential for the productivity of floodplain agriculture and river fisheries (*21*). Additionally, dams fragment river systems by blocking the movement of migratory fishes that are the mainstay of Amazon fisheries, which provide important sources of nutrition and livelihoods to local inhabitants (*22*–*24*). River connectivity loss also interferes with traditional riverboat transport of people and goods on which riverside communities rely. Further, reservoirs created by dams generate greenhouse gas emissions, an ecosystem disservice in that minimizing carbon intensity is one of the central considerations of energy planning (*25*). While hydropower is often viewed as a less carbon intensive energy source, some reservoirs emit as much greenhouse gases as the equivalent energy generation from fossil fuels (*14*, *26*).

Our approach determines the Pareto-optimal frontier, which represents a set of solutions (i.e., portfolios composed of different configurations of dams) that minimize negative effects across environmental objectives for any given level of aggregate hydropower yield. This optimization problem is computationally intensive because it requires accounting for 2^{509} (~10^{153}) possible combinations of the 509 current and proposed dams in the Amazon basin. To overcome this challenge, we developed a fully polynomial-time approximation algorithm based on dynamic programming that, unlike previous heuristic approaches, can quickly approximate the Pareto frontier for multiple environmental criteria simultaneously and with guarantees of theoretical optimality (*27*–*29*). Given the vast number of Pareto-optimal solutions and the limitations of human cognition to visualize high-dimensional spaces such as a six-dimensional Pareto frontier, we developed an interactive graphical user interface (GUI) to navigate the high-dimensional solution space for Amazon dams (see materials and methods section 2.5 in the supplementary materials) (*30*).

Optimization across all dam sites to achieve current levels of hydropower production shows that the historical lack of strategic basin-wide planning has produced a configuration of dams that is far from optimal from an environmental perspective. We calculated the chronology of ecosystem impacts during the historical expansion of hydropower dams throughout the Amazon basin (which measures >6.3 million km^2) and compared the actual trajectory of environmental degradation under historical energy development against the original Pareto frontier, which we define as the hypothetical Pareto frontier for all existing and proposed dam sites. The difference between the historical trajectory and the original Pareto frontier represents the forgone ecosystem benefits of basin-wide planning, which were computed separately for each environmental criterion. Criteria such as river connectivity, based on a dendritic river connectivity index (RCI_P) that quantifies drainage network fragmentation, have changed drastically from the initial historic pre-dam baseline (Fig. 2A). River connectivity throughout the Amazon remained relatively intact until recently, with a loss of <10% between 1914 (when the first dam was built in the basin) and 2012. However, the blockage of major tributaries by construction of two large dams on the Madeira River (Santo Antônio and Jirau, completed in 2012 and 2013, respectively) and the Belo Monte dam on the Xingu River (completed in 2016) has led to abrupt and steep declines in river connectivity. These three recent projects, among the largest in the world, have increased fragmentation of the Amazon River network by nearly 40% in the past decade alone. Comparing the existing and baseline Pareto frontiers illustrates that other dam configurations could have delivered equivalent amounts of hydropower capacity as exists today in the Amazon, with relatively little loss in connectivity (Fig. 2A). Indeed, coordinated planning could have produced up to four times as much hydropower without exceeding the current level of connectivity loss. Loss of network connectivity is the most conspicuous case of forgone benefits; the impact of historical dam construction on flow regulation and other criteria falls much closer to the original Pareto frontier for achieving current hydropower production (Fig. 2), demonstrating the heterogeneous impacts of dam development among different ecosystem services.

The enormous differences in environmental impact per unit of electricity production illustrated by our Pareto frontier analyses underscore the need for strategic, basin-wide planning of any future hydropower expansion based on many criteria. Both computational challenges and data limitations have constrained previous

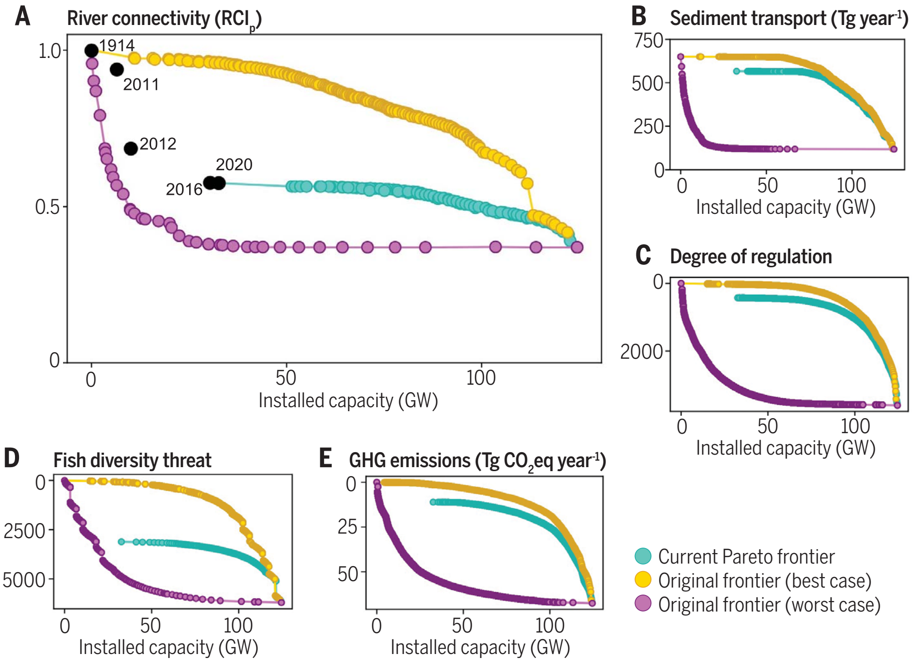

Fig. 2. Forgone environmental and energy benefits of uncoordinated dam planning in the Amazon. Pareto-optimal solutions for Amazon hydropower development based on electricity generation and different environmental criteria. For each environmental criterion (**A** to **E**), the plots show the original best-case scenario that could have been achieved with optimal planning from the commencement of dam building in the Amazon (yellow) compared with the original worst-case scenario (purple) for hydropower placement; black filled circles show the chronological trajectory of existing dams, whereas the cyan line shows the current possible best-case scenario for optimal hydropower placement moving forward from current conditions in 2020 for proposed dams considering (A) river connectivity, (B) sediment transport, (C) cumulative downstream flow alteration estimated using a degree of regulation index (values are the sum of degree of regulation for each dam portfolio), (D) fish diversity threat score, and (E) greenhouse gas emissions from reservoirs.

basin-wide hydropower planning to include only one or a few environmental objectives at a time (*14*, *31*–*34*). Yet rivers provide suites of ecosystem services that are potentially affected by damming, and jointly considering multiple criteria can substantially alter optimization outcomes. In contrast to two-dimensional Pareto frontiers exploring trade-offs between only energy production and connectivity (Fig. 3A), simultaneous consideration of additional criteria (sediment delivery, degree of regulation, fish diversity, greenhouse gas emissions) results in large changes in the identity and frequency of particular dams occurring within optimal dam portfolios. These changes in optimization outcomes ensue because trade-offs emerge among river ecosystem services (Fig. 3A). For example, optimal solutions for river connectivity include many high-elevation dams at sites farthest away from the mouth of the Amazon; consequently, dams in the high Andes are often included in Pareto-optimal solutions when optimizing only for river connectivity (Fig. 3B). Conversely, Andean-sourced rivers produce most of the nutrient-rich sediment in the Amazon River that sustains productivity and structures the geomorphology of the floodplains (Fig. 1D); accordingly, dams in Andean-sourced rivers interrupt sediment transport more substantially and are therefore rarely included in Pareto-optimal solutions for sediments alone (Fig. 3B). Thus, replacing one environmental criterion with another can greatly modify the frequency with which some dams are Pareto optimal (Fig. 3A). Notably, ~60% of proposed Amazon dams always appear in Pareto-optimal solutions for certain environmental criteria while never appearing in optimal solutions for others (Fig. 3B). Owing to this large incongruence among objectives, optimizing dam planning for a single environmental criterion inevitably results in suboptimal performance for other environmental criteria (Fig. 3C). This case is clearly illustrated when comparing the sediment transport outcomes optimized for river connectivity against those attained when optimized directly for sediments. For example, the 80 GW dam portfolio planned optimally for river connectivity would trap a far larger proportion of sediments basin-wide than the 80 GW dam portfolio planned optimally for sediments (Fig. 3C).

Basin-wide planning outcomes

As more environmental criteria are evaluated simultaneously, we observe further complexity in optimization outcomes. Consequently, when all five of our environmental criteria are considered in a six-dimensional Pareto frontier, few dams remain that are frequently Pareto optimal (Fig. 3A) (*30*). In addition, a diversity of trade-off outcomes among environmental criteria are revealed by the six-dimensional Pareto frontier (Fig. 3D) (*30*). For example, our algorithm identifies ~30 optimal solutions for a hydropower target of 80 GW, but these equivalently optimal dam portfolios can result in vastly dissimilar environmental performance for different individual criteria (Fig. 3D). Given the sharp trade-offs among environmental objectives that become evident with multiobjective optimization, certain criteria may be given more weight depending on the values of society and decision-makers. Regardless, basin-wide strategic planning needs to consider suites of multiple criteria simultaneously, recognizing that the chosen set of criteria can alter our perception of "high-impact" versus "low-impact" dams.

Yet another challenge in strategic hydropower planning is its dependence on the spatial scale of analyses. To quantify the importance of spatial scale, we conducted a set of analyses at subbasin, regional, and whole-basin scales. We ranked all proposed dams according to the frequency with which these projects appear in at least 50% of Pareto-optimal solutions, with higher frequencies indicating less detrimental environmental outcomes in aggregate. For example, when Pareto-optimal solutions are evaluated for sediment transport at the western Amazon scale (Marañón, Napo, and Ucayali subbasins), ~32% of proposed dams (36 of 114 dams) appear in at least half of the Pareto-optimal portfolios (Fig. 4). In contrast, when optimizing for sediment transport at the scale of the entire Amazon basin, fewer than 20% (21 of 114) of these same dams appear in at least half of the Pareto-optimal portfolios (Fig. 4). Moreover, while ~48% of the proposed Tapajós River dams (70 of 144 dams) appear in at least half of the Pareto-optimal portfolios at the Tapajós optimization scale, nearly all of these same dams (142 of 144) are included at the whole-basin scale. The clear-water Tapajós River originates in Precambrian shields in the eastern Amazon and is characteristically sediment poor, whereas western Amazon rivers drain geologically younger terrains in the Andes and are notoriously sediment rich (*21*, *35*). Consequently, Tapajós dams fare better when optimizing for sediment at larger spatial scales that include consideration of dams in sediment-rich rivers. These findings build on previous efforts showing that Amazon subbasins differ in their vulnerabilities to dams on the basis of different hydrophysical features and biotic diversity (*12*, *36*) and bolster the notion that planners and decision-makers need to consider how spatial scale influences their perceptions of better solutions with respect to different environmental criteria.

Our results illustrate how strategic, basin-wide planning enhances the probability of selecting dam configurations with less destructive, aggregate environmental outcomes. In practice, however, hydropower planning generally occurs at the national scale, even though electricity may be exported across borders, for example from the Andean Amazonian countries to Brazil. We assessed the potential of international cooperation to improve environmental outcomes by comparing basin-wide Pareto frontiers with those based on country-level optimal planning for each of our five environmental criteria. Clear opportunities exist for reducing environmental costs through international cooperation (Fig. 5). For example, developing 50% of the proposed hydropower potential optimally on a country scale but without international coordination would result in trapping substantially more sediments on a basin-wide scale (Fig. 5A). For all Amazonian countries, optimal planning at the country scale yields suboptimal environmental outcomes at the whole-basin scale for at least one of our five environmental criteria (Fig. 5B). Further, dam sites that are disfavored in a country-scale analysis can be strongly favored in Amazon-wide optimization. This disparity in site prioritization between different scales is especially notable for proposed dams in Ecuador. Because almost all Ecuadorian dams are run-of-river projects located in the Andes at mid to high elevations in the far western Amazon basin, they would fragment comparatively short river segments (*22*), yield relatively small greenhouse gas emissions (*14*), and are often situated in montane zones beyond the distributional limits of diverse Amazon fish assemblages. However, our analyses only consider environmental criteria and do not include other factors such as seismic risk and long energy transmission distances that could make dams in Ecuador much less satisfactory when a broader suite of planning objectives is considered.

Conclusion and prospects

Enhanced computational capabilities are unlocking the potential for strategic, basin-wide planning to guide dam site selection during hydropower expansion. Our quantitative analysis shows how, in the absence of basin-wide integrated environmental assessments, historical dam-by-dam decision-making has resulted in large forgone ecosystem benefits (Fig. 2). The comparison of the original Pareto frontier for all existing and proposed dams with historical patterns of hydropower development underscores the adverse consequences of uncoordinated planning in the Amazon. On the basis of these findings, we highlight four key principles for reducing the environmental costs of hydropower expansion.

First, multiobjective optimization provides an effective first filter to identify dams that would be particularly detrimental and can be a valuable step for strategic and integrated environmental assessments (*16*, *37*). However, a notable limitation has been the inability to apply strategic environmental assessments to all hydropower potential across large areas

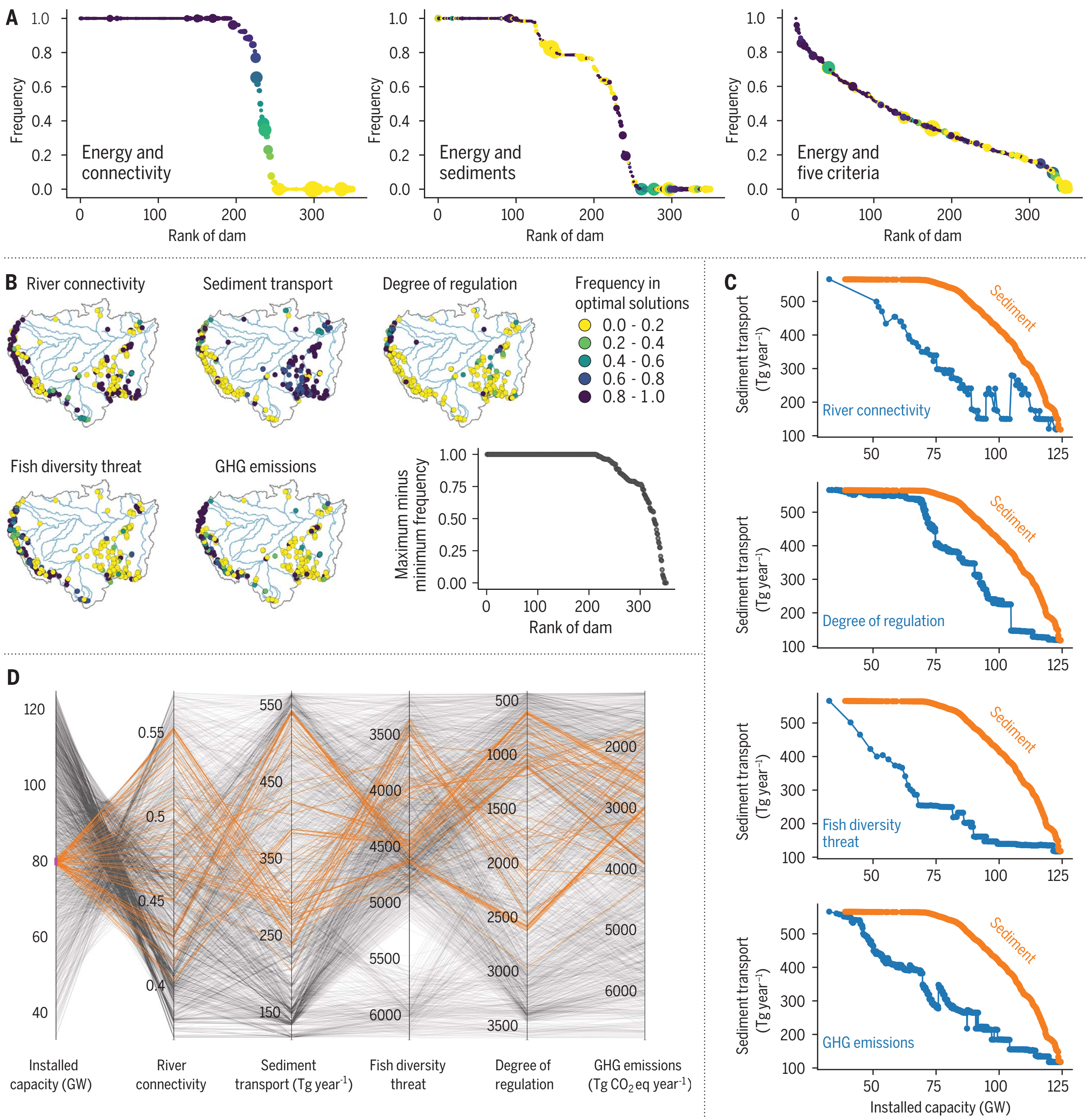

Fig. 3. The importance of choice of criteria for strategic hydropower planning. (**A**) Rank frequency plots showing the frequency with which each of the 351 proposed Amazon dams appears in optimal solutions for trade-off analyses between energy and river network connectivity, sediment transport, and all five environmental criteria considered simultaneously; dams in the middle and right-hand plots are colored according to their frequency in optimal solutions (purple, high frequency; yellow, low frequency) compared with when only energy and connectivity are analyzed (left-hand plot), and dot sizes are proportional to installed capacity. Note that as more objectives are considered, fewer dams are in Pareto-optimal solutions owing to trade-offs among criteria. (**B**) Maps showing the frequency with which each dam appears in optimal solutions for each environmental criterion when criteria are optimized individually; the bottom-right plot shows the difference between the maximum and minimum frequencies in optimal solutions among the five criteria for each dam, with the 351 dams ranked from highest to lowest values. (**C**) Basin-wide sediment transport outcomes of Amazon dam portfolios planned optimally to minimize sediment retention in comparison to sediment outcomes attained when optimizing individually for each of the other four criteria (river connectivity, degree of regulation, fish diversity, and greenhouse gases). (**D**) Parallel coordinate plot with solutions that are Pareto-optimal for all criteria simultaneously. Each coordinate corresponds to a criterion, and each line connecting different values along the coordinates corresponds to a single Pareto-optimal solution; all optimal solutions for 80 ± 0.5 GW are highlighted in orange. GHG, greenhouse gas emissions.

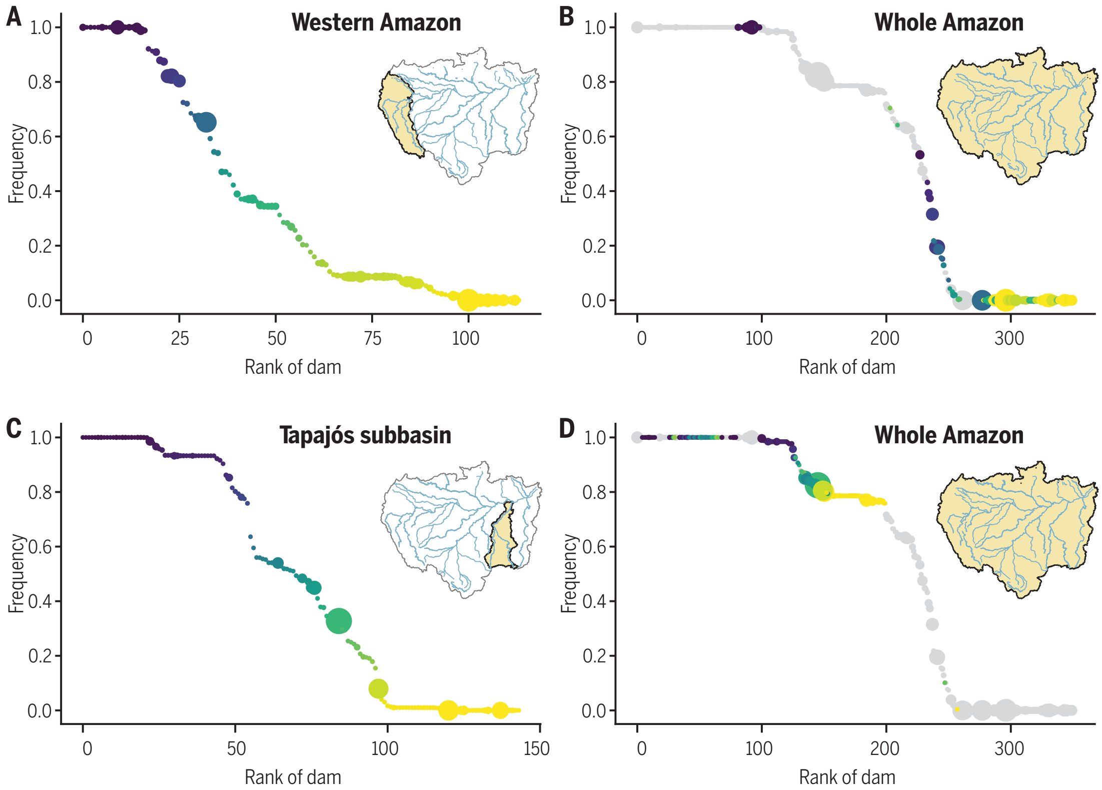

Fig. 4. The importance of spatial scale for strategic hydropower planning. Rank frequency plots showing the frequency with which each of the 351 proposed Amazon dams appears in optimal solutions for trade-off analyses between energy generation and sediment transport. (**A**) Rank frequency plot showing the frequency with which proposed dams in three western Amazon subbasins (Marañón, Napo, and Ucayali rivers) are in configurations along the Pareto-optimal frontier. (**B**) Frequency with which the same proposed western Amazon dams are in optimal solutions when analyzed at the scale of the entire Amazon basin; dams are colored according to their frequency in optimal solutions at the western Amazon scale (purple, high frequency; yellow, low frequency). (**C** and **D**) Same as (A) and (B), but for the Tapajós subbasin. Note the contrasting effects of increasing spatial scale of analysis for western Amazon subbasins with high sediment loads as opposed to the Tapajós subbasin with little sediment load. Dot sizes are proportional to installed capacity.

(*16*), and here we provide advanced computational methods for basin-wide assessment at the scale of the world's largest river network. Traditionally, energy and economics drive the selection of hydropower projects, with environmental impacts assessed subsequently during the licensing process for select individual dams. By identifying projects that approach the worst-case development trajectory, our analysis can screen out proposed dams with highly adverse environmental risks. In addition to foreseeable environmental consequences, these same high-impact projects often carry large social and economic risks, increase investment uncertainty, and contribute to considerable cost overruns and substantial time delays (*38*), highlighting the utility of effective first filters. Environmental impacts are often viewed as economically expensive roadblocks to energy development; instead, by marshaling extensive environmental data as part of a first filter, our approach can serve the mutual benefits of avoiding far-reaching and costly socioenvironmental impacts in the context of meeting broader energy goals, thereby helping inform more-sustainable solutions (*39*).

Second, simultaneous consideration of multiple criteria is critical for identifying the least detrimental projects (Fig. 3). The importance of evaluating trade-offs involving multiple criteria has long been recognized in the context of sustainable development goals and the management of ecosystem services (*40*, *41*). However, previous quantitative approaches could not scale up to handle a large number of criteria at the scale of the entire Amazon with optimality guarantees; here we quantify the marked disparities in seemingly optimal portfolios that ensue as more criteria are considered. As a broader suite of criteria are evaluated, increasingly complex trade-offs among criteria sharply curtail the number of dams consistently identified as low impact. Although we focused on five heuristically valuable environmental criteria, we recognize that additional objectives (political, economic, social, environmental) need to be included for overall strategic hydropower development planning (*8*, *37*). Optimizing variables that integrate a set of related services into bundles (*7*, *12*, *36*) may also be effective in advancing strategic hydropower planning and minimizing challenges associated with complex trade-offs among criteria. Further considering uncertainties in river basin planning—such as climate change, disruptions in governance, and adoption of alternative energy sources including wind and solar (*42*–*46*)—will be critical before embracing hydropower expansion in the Amazon, because these are likely to shape trade-offs among criteria. In addition, site-scale optimization of operations can partly mitigate some of the adverse effects of poor dam placement (*47*). Currently, it is not possible to include operations at a basin-wide scale, because few details are known for most Amazon dams that have not yet reached an advance planning stage; changes in operational rules made during the licensing process further compound this limitation. As more data become available for inclusion in our computationally efficient approach, more-informed strategic hydropower planning will lead to better outcomes for nature and people.

Third, in large and complex river systems, basin-wide analysis is essential for minimizing forgone benefits. Optimization of dam site selection at national, subbasin, and whole-basin scales often yields conflicting results for particular projects because the pool of candidate dams increases with area, and the perspective of the magnitude of impacts in any region can be modified by changing geographical scale (Figs. 4 and 5). This creates risk of uninformed decision-making, as seemingly low-impact dams based on optimization at the subbasin or country level can in reality be highly problematic when assessed at a whole-basin scale. Yet, whole-basin planning requires new tools and perspectives and is especially complicated when rivers cross political boundaries. Our use of artificial intelligence with optimality guarantees to consider the impacts of all

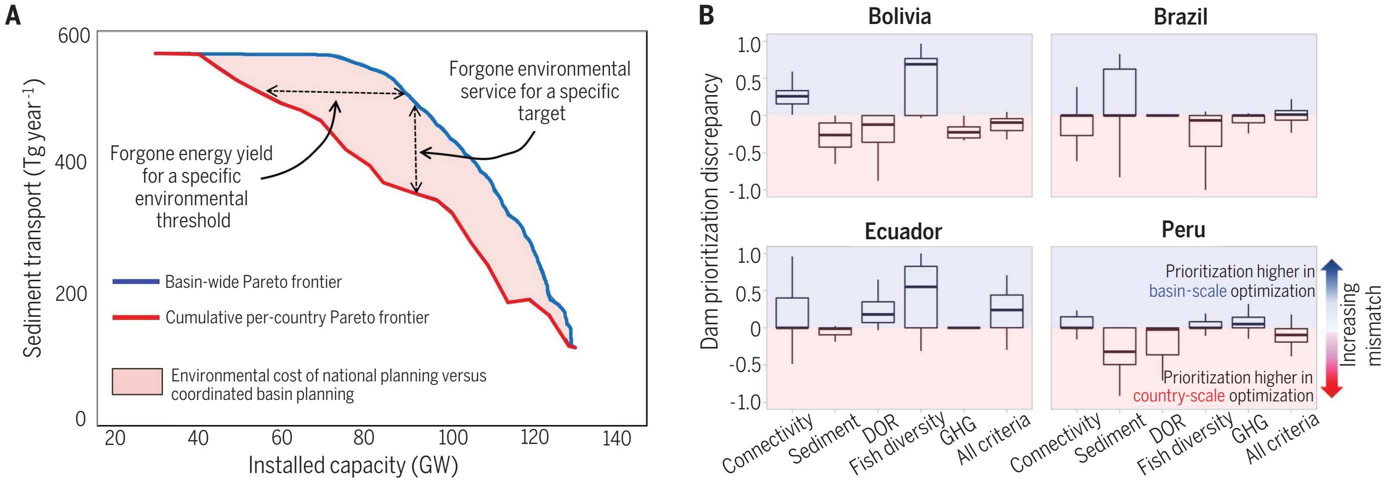

Fig. 5. International cooperation among Amazonian countries can lead to more-efficient strategic hydropower planning outcomes. (**A**) Pareto frontiers for cumulative country-level (red line) and basin-wide (blue line) optimizations for sediment transport. For country-level analyses, each country contributes an equivalent proportion of its own proposed hydropower potential toward meeting basin-wide energy generation targets. The difference between basin-wide and country-level lines illustrates the environmental and hydropower costs of the lack of basin-wide strategic planning. (**B**) Disparities in the frequency with which individual dams appear in optimal solutions when planning occurs at the basin-wide scale versus the country scale for each criterion and all criteria simultaneously. Box and whisker plots are shown for five environmental criteria run for four Amazonian countries (Bolivia, Brazil, Ecuador, and Peru) that make up >90% of the area of the Amazon basin. Values near zero indicate concordance between country-scale and whole-Amazon assessment of dam prioritization. Dams that are often included in basin-wide planning but that are rarely included in country-level planning (positive values) and vice versa (negative values) indicate a potential mismatch between countries' hydropower dam selection priorities and those that are preferable for minimizing basin-wide ecosystem service impacts. Mismatches in dam priorities across scales also vary depending on the criteria used for multiobjective optimization, indicating that coordination on the selection of planning criteria is also an important feature of cooperative pan-Amazon dam planning. DOR, degree of regulation. The horizontal lines inside the box and whisker plots indicate the median, and the boundaries indicate the 25th and 75th percentiles. For improved visualization, outliers are not shown.

possible dam portfolios is complementary to other approaches for assessing regional-scale impacts of Amazon dams that identify subbasins and geological-physiographic domains where environmental consequences are likely to be most acute (*12*). Although we stress the importance of system-scale risk screening, this does not preclude the essential role of local stakeholder interests in guiding dam siting, once the potentially most detrimental projects are removed from consideration.

Finally, international cooperation is paramount for reducing adverse impacts of hydropower expansion in transboundary basins (Fig. 5). Without a basin-wide approach to planning, and requisite decision-support tools, a sustainable path for energy development in the Amazon will remain elusive. Coordinated planning moving forward is challenging and requires mechanisms for cooperative agreements and their enforcement. For example, the Amazon Cooperation Treaty Organization has existed for nearly two decades as a forum for cooperation and dialog among Amazonian countries to promote sustainable development (*48*), but this transboundary policy instrument has yet to be adequately leveraged to enhance the scale and caliber of integrated environmental assessments of Amazon hydropower (*12*). The Leticia Pact, signed in 2019, provides a fresh opportunity for a whole-basin approach to guide cooperation among Amazonian countries through mutual agreements regarding sustainable Amazon development (*49*). An encouraging step is the recent launch of the Amazon Regional Observatory as a platform for sharing information pertinent to environmental resource management and biodiversity conservation (*50*), which should provide additional data needed for whole-basin planning. Moreover, Brazil has begun to deploy integrated environmental assessment at subbasin scales, and the existence of such regulatory frameworks could provide a blueprint for upscaling to more extensive planning (*16*). In addition to improved policy mechanisms and greater data availability, breakthroughs in computer science will lead to more opportunities to develop novel decision-support tools for building more-sustainable integrated energy systems (*10*). The data and tools produced by this study can provide unbiased input to such policy instruments, assuming political leaders and financial institutions are committed to collective benefits of basin-wide strategic planning for hydropower expansion in transboundary river basins.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S6
Tables S1 to S3
References (*51*–*98*)
MDAR Reproducibility Checklist
Data S1 and S2

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Science

Reducing adverse impacts of Amazon hydropower expansion

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Planning for Amazonian hydropower
Hydropower projects are proliferating in many parts of the world. The benefits they bring in electricity supply are often offset by environmental costs. In an international collaboration, Flecker *et al*. present a study that aims to optimize the retention of ecosystem services in the face of hydropower expansion in the Amazon basin (see the Perspective by Holtgrieve and Arias). The authors found that simultaneous consideration of multiple criteria (sediment transport, river connectivity, flow regulation, fish biodiversity, and greenhouse gas emissions) is necessary for optimizing the size and location of dams, and that the geographical scale of planning is also key (benefits from a smaller-scale plan may be detrimental at the basin scale). Their computational method allows the evaluation of each trade-off individually or all trade-offs simultaneously and is broadly applicable in other basin settings. —AMS

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