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Impacts of climate change and deforestation on hydropower planning in the Brazilian Amazon

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The Amazon Basin is Brazil's next frontier for hydropower, but alterations to the water cycle from climate change and deforestation could affect river flows fuelling electricity generation. This research investigated the effects of global and regional changes to the largest network of planned and existing dams within a single basin in the Amazon (the Tapajós River), which altogether accounts for nearly 50% of the inventoried potential expansion in Brazil. Future hydrological conditions could delay the period of maximum daily generation by 22–29 d, worsening the mismatch between seasonal electricity supply and peak demand. Overall, climate change could decrease dry season hydropower potential by 430–312 GWh per month (−7.4 to −5.4%), while combined effects of deforestation could increase interannual variability from 548 to 713–926 GWh per month (+50% to +69%). Incorporating future change and coordinating dam operations should be a premise in energy planning that could help develop more resilient energy portfolios.

The provision of electricity from renewable energy sources is one of the United Nations' Sustainable Development Goals that could have the greatest impacts on climate change mitigation and humanity's wellbeing. Hydropower accounts for nearly 77% of the world's renewable electricity generation and its dominance among renewable sources is projected to continue for the foreseeable decades[1]. Most of the newly installed and proposed hydropower capacity is occurring in countries with emerging economies; in 2015, for instance, 33.3 GW of hydropower capacity were installed in China, Brazil, Turkey, India, Iran, Vietnam, Malaysia, Colombia, Laos and Ethiopia, accounting for 90% of the world's total added that year[2].

Although the re-emergence of large dams could bring large energy, economic and climate change mitigation incentives to growing national economies, these will come at the expense of altering the natural flow regime of rivers[3,4] that is responsible for biodiversity, ecological and agricultural productivity, as well as the cultural value of these aquatic systems and their floodplains[5]. These trade-offs between national hydropower and local ecological and cultural values are particularly sensitive in the Amazon, Mekong and Congo river basins, the three most biologically diverse rivers on Earth, which are current epicentres of large-scale hydropower development[6,7]. Several efforts have quantified trade-offs among hydropower generation, hydrological alterations and ecosystem services in these river basins at local to regional scales[8–14], making it possible to identify regions and particular locations where improvements could be made to increase the overall sustainability of hydropower projects.

The role of climate and land cover change in energy planning in emergent economies remains a critical and puzzling issue that could play a major role in the sustainability of hydropower. This is particularly true for the Amazon, where major environmental changes associated with the changing climate and deforestation are expected to occur[15–20]. If warming and total deforestation reached thresholds of +4 °C and 40%, respectively, these could lead to tipping points with deep detrimental consequences to the Amazon's biodiversity, carbon storage and water cycle[21]. Indeed, past research demonstrated that deforestation could affect the water cycle in both direct and indirect pathways, altering the hydropower potential of Belo Monte, the largest dam in the Amazon[22]. How deforestation, in combination with climate change, could affect hydropower generation in a broader and substantial portfolio of dams remains an open and timely question.

The main objective of this study is to quantify the effects of the Amazon's main environmental drivers of change—climate change and deforestation—on hydropower generation, and to identify mechanisms that could help energy planners to account for changes in coming decades (2026–2045). This study connects global and regional future environmental projections to daily river flows and operations of 37 existing and planned dams in the Tapajós basin (Fig. 1) that represent nearly half of Brazil's inventoried potential hydropower capacity. This relationship was quantified through a series of numerical models that accounted for effects of ecosystem dynamics in energy and water fluxes, water flow routing through the landscape, and hydropower infrastructure and operations. Although it focuses on a subregion of the Amazon, the methodology and recommendations for energy planning proposed in this paper are relevant to other Amazonian countries and other tropical regions where the integrity and sustainability of the new wave of hydropower development could be compromised by the changing climate and land-use conversion.

Inventoried installed capacity versus future potential power

The cumulative capacity of inventoried projects (existing and planned) in the Tapajós basin is 29,434 MW, which represents 27% of Brazil's current installed hydropower capacity or 43% of all

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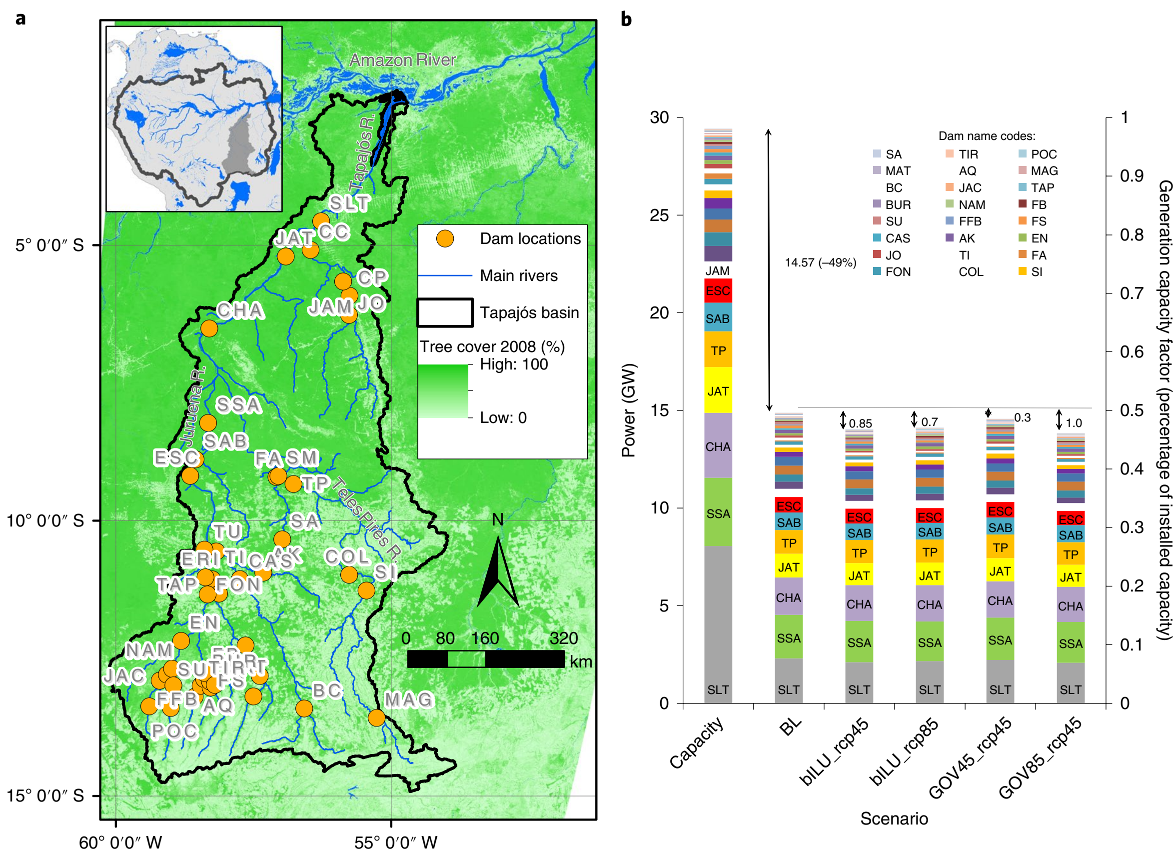

Fig. 1 | The inventoried capacity of 37 existing and planned dams in the Tapajós basin could be 29.4 GW, equivalent to 27% of Brazil's current installed capacity. **a**, Overview map of the study location, with basemap displaying 2008 tree cover as derived from MODIS imagery[52]. **b**, Proposed cumulative installed capacity compared to potential power for historical hydrological conditions (BL), future scenarios of climate change alone (bILU_rcp45 and bILU_rcp85) and climate change with deforestation (GOV_rcp45 and GOV_rcp85). Power potential in the BL could be as low as 51% of the total capacity but a reduction of 0.32–1.04 GW could be expected, depending on future hydrological conditions. Codes used for dam names are defined in Supplementary Table 1. Delineation of rivers and watersheds based on data from HydroSHEDS[53,54].

planned development in the country's inventory[23]. These estimates of installed capacity, however, do not provide an accurate account of the actual potential contribution of these hydropower projects to the electrical grid (generation capacity factor), which once historical flow seasonality and interannual variability are considered, could only account for 51% of the installed capacity (Fig. 1). When future climate and deforestation scenarios are considered (see detailed scenario description in the Methods), this percentage could be even less (47–49%), corresponding to a loss of 316–1,044 MW (2,951–9,303 GWh yr^{-1}). For reference, Itaipu, Brazil's largest hydropower dam, has an installed capacity of 14,000 MW, mean annual production of ~95,000 GWh, and an annual generation capacity factor over 90% (ref. [24]). The relatively low generation factor of dams in the Tapajós basin is typical of run-of-the-river dams (as most of the dams planned in the Amazon lowlands), which are designed with little operational water storage and rely primarily on instantaneous river flows to power turbines.

Future rainfall shifts could affect hydropower generation

Rainfall seasonality has been shifting in the South Amazon since the 1970s[25] and future climate change projections indicate a net annual rainfall reduction in the region by up to 20% in combination with a further delay of the wet season by about 1.5 months[18]. Overall, this study shows that climate-driven changes could have a greater impact on the magnitude of electricity generation of dams in the Brazilian Amazon; deforestation plays an important role in altering peak annual flows and increasing interannual hydrological variability[18] but changes to peak flows would not affect generation in this predominantly run-of-the-river dam network, in which hydropower production is limited by the installed capacity of turbines designed for average wet conditions (Fig. 2). Overall, future scenario simulations show that energy generation could notably change from baseline for every month of the year, irrespectively of the scenario (Fig. 2). Because of terrain and environmental constraints, dams included in this study will have reservoirs with limited storage volumes, which on average could hold water for ~14 d. Consequently, peak daily generation capacity of dams in this study (~507 GWh) could only be achieved during 93 d of the year, from early March to early June. Future climate change could delay this peak period by 22–29 d. Because this shift is expected to be longer than the nominal residence time of water in the reservoirs, the operational (active) storage will not be sufficient to counteract the seasonal shift driven by climate change. This shift could have important implications for energy planning in Brazil. Most of the new and proposed installed generation capacity relies on seasonally varying sources, mainly run-of-the-river hydropower and wind power. Run-of-the-river dams, in particular, are good alternatives to fulfil Brazil's seasonal peak demand, historically occurring in February–March during the late summer in the southeast of the country, where most of the population and industrial activity reside. With the expected mismatch between the seasonal supply of energy and the country's peak demand, the energy sector could face challenges if these future

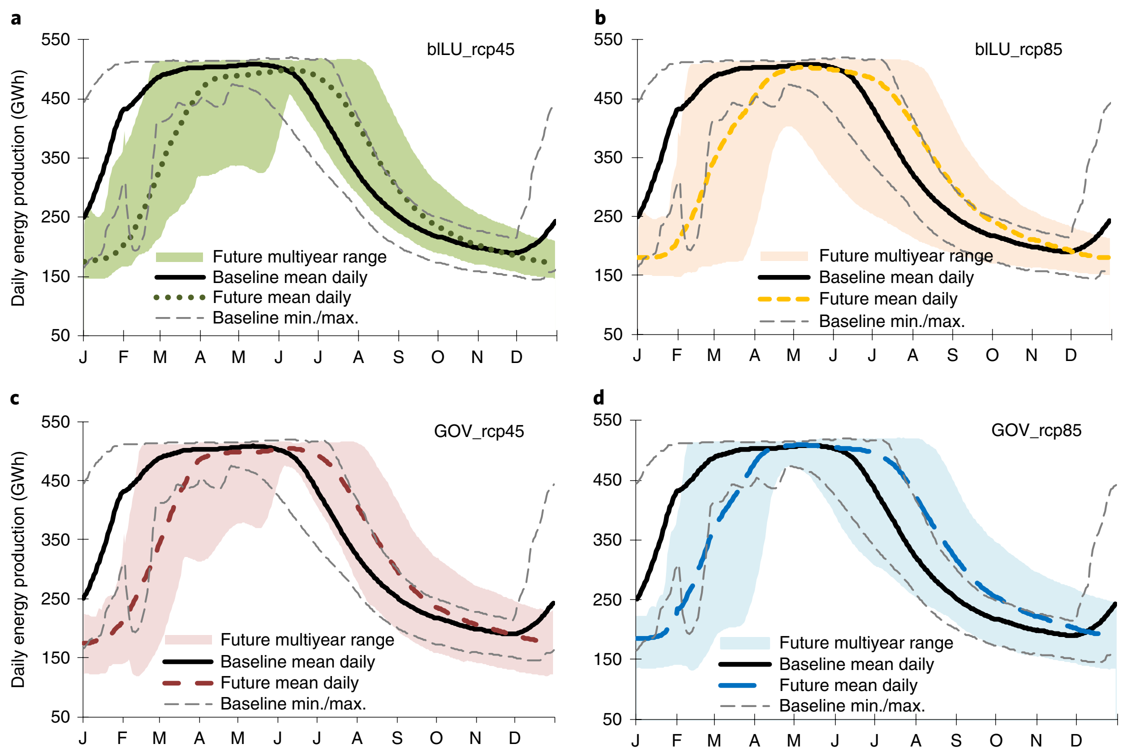

Fig. 2 | Climate change could drive a >1-month shift in the seasonal peak of daily electricity generation of dams in the Tapajós basin, which will have implications for Brazil's energy planning. a, Effects of moderate future climate change (scenario blLU_rcp45). **b**, Effects of extreme future climate change (scenario blLU_rcp85). **c**, Combined effects of moderate future climate change with moderate deforestation (scenario GOV_rcp45). **d**, Combined effects of extreme future climate change with moderate deforestation (scenario GOV_rcp85). The Kolmogorov–Smirnov non-parametric statistical test revealed that production in all four future scenarios is statistically different ($P < 0.01$) from the corresponding month in the baseline scenario. A more detailed explanation of scenarios is provided in the Methods. Months shown on *x* axes as J, January through to D, December.

changes are not considered in the planning process. This aspect is critical due to the low degree of regional interconnection between Brazil and neighbouring countries, which makes energy self-sufficiency essential[26].

Increasing hydropower vulnerability during dry periods

Results from the seasonal patterns of hydropower production suggest a net electricity reduction during dry periods. Losses in hydropower production during the dry season could be problematic to operators, who could already be functioning at 27% of installed capacity (7,936 of 29,434 MW) during this time of the year (summer months in Brazil's southeast) when demand is maximum. To further explore this issue, the month of minimum power generation for each year was estimated (Fig. 3). We found that climate change could further decrease hydropower production by 430–312 GWh per month (−7.4 to −5.4% from baseline historical conditions). As it was demonstrated by the alarming water scarcity that affected more than 85 million people in the southeast during 2014–15[27], Brazil's water sector is already highly vulnerable to drought. The magnitude and variability of dry periods, however, is likely to increase in Brazil's Eastern Amazonia[17–19,28,29], and if such projected anomalies are not considered in future water resources and energy planning, Brazil could face even more drastic shortages than it has already experienced in the recent past.

In addition to effects on the magnitude of minimum monthly hydropower generation, future scenarios could also exacerbate interannual variability (Fig. 3). While the estimate for baseline conditions is 548 GWh per month, interannual variability in minimum monthly generation could increase to 578–713 GWh (+5 to +30%) in scenarios of climate change alone (blLU_rcp45 and blLU_rcp85) and to 822–926 GWh (+50% to +69%) in scenarios of combined deforestation and climate change (GOV_rcp45 and GOV_rcp85). The additional increase in variability from deforestation is sufficient to mask the net negative effect of climate change on magnitude of generation, as has already been documented for past and future streamflows in the Tapajós basin[18,30]. The increase in variability due to deforestation also means that there could be years when hydropower generation during the minimum production month may be 9–18% lower in the future than under baseline conditions. Overall, the projected increase in variability during dry periods caused by deforestation implies that efforts to prevent further forest clearance in dam watersheds could result in more reliable hydropower generation during this critical time of the year.

Dam prioritization based on future electricity generation

Understanding basinwide impacts of climate change and deforestation on hydropower is critical to determine overall regional risks but there also needs to be an assessment of individual dam contributions, compatible with the existing process of hydropower project selection and prioritization. Currently, this process is based on potential installed capacity at each location, given limited historical hydrological records. We propose that as part of this process, expected gains/losses and uncertainty associated with future hydrological conditions are considered to assess the most likely long-term performance of hydropower projects. In the case of the Tapajós basin, a careful consideration of future hydrological conditions on individual dams highlights that, in general, projects with the largest potential are also the ones that could result in the highest risk to energy planners because of the large magnitude and uncertainty of future losses (Fig. 4). For instance, São Simão Alto

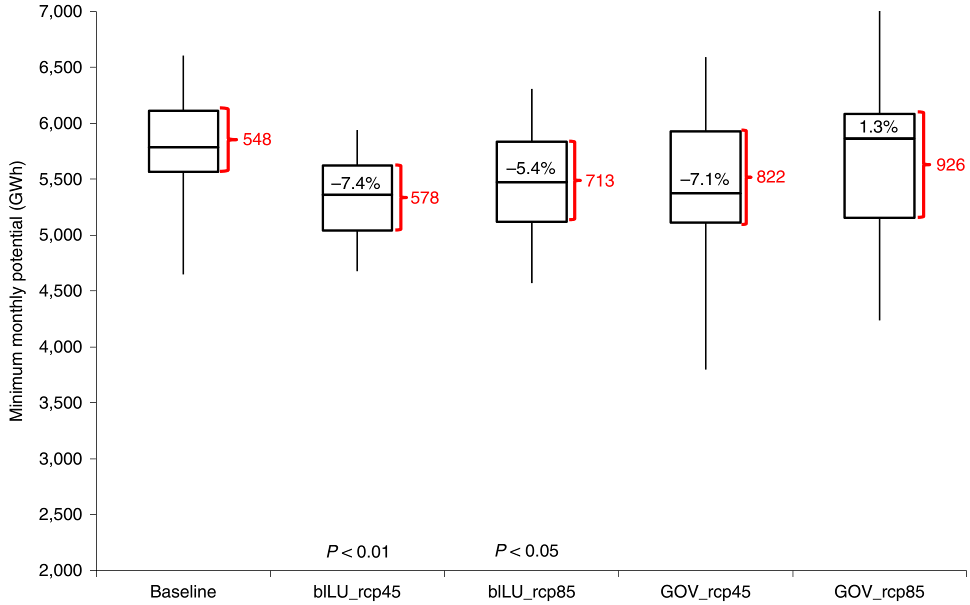

Fig. 3 | Electricity generation during the minimum month per year is expected to decrease in magnitude and increase in variability. Numbers in black represent the change in 50th percentile, while numbers in red represent the interquantile range in annual variability (in GWh per month). Vertical lines represent the spread of data ($n = 21$) for each scenario. P values correspond to the statistical (t-test) comparison between the baseline and the climate change scenarios.

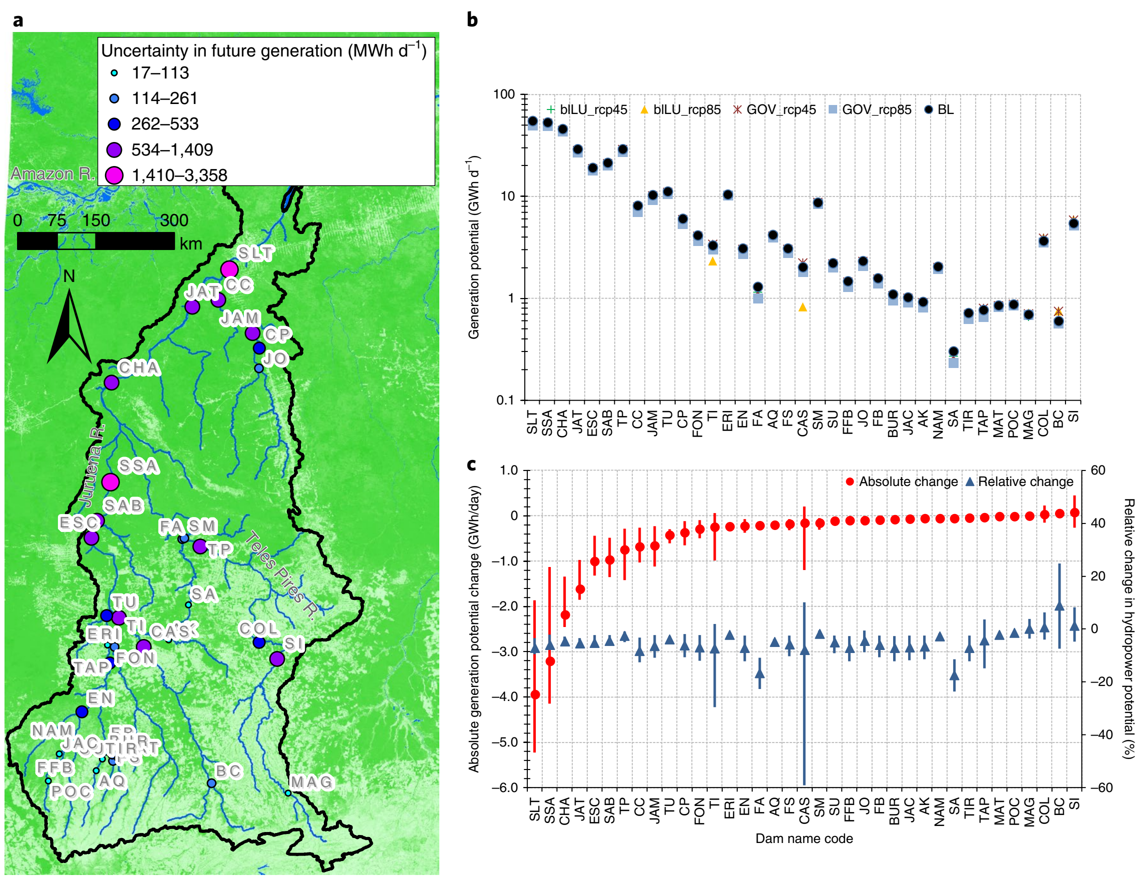

Fig. 4 | Understanding the future performance of individual dams can help to identify vulnerable projects that may not meet their expected contribution to the national electricity grid. a, Location of dams coloured and sized according to uncertainty in future generation change (the difference in mean daily generation between the best and the worst future scenario). Sources of geospatial data are the same as in Fig. 1. **b**, Expected hydropower generation of individual dams under specific future scenarios. (Note that there is overlap among future scenarios for a number of dams.) **c**, Scenario-driven variability in hydropower potential, both in absolute terms (left axis) and relative to baseline historical conditions (right axis). Codes for dam names are defined in Supplementary Table 1.

(SSA in Fig. 4) could generate on average 53.37 GWh d^{-1} assuming historical conditions but future changes are expected to result in a net loss of 1.13–4.14 GWh d^{-1}. Similar magnitude and uncertainty of losses were found for 11 of the 37 dams studied. Among these 11 dams, Castanheira and Travessão dos Indios (CAS and TI in Fig. 4) could experience large losses relative to baseline historical conditions, since they are large projects (installed capacity of 192 and 252 MW) located in the middle basin (Juruena River) where river flow is expected to decrease substantially in the controlled deforestation-high emissions climate change scenario (blLU_rcp85). For 21 of the remaining dams, generation losses of 0.013–0.15 GWh d^{-1} are expected for all future scenarios. For the other five dams, the range of change in potential power could be +0.024 GWh d^{-1} on average (range of −0.032 to +0.072 GWh), since these are smaller dams located in the upper basin that may experience a marginal increase in runoff due to deforestation. Overall, this information on future changes to performance of individual dams could help in prioritizing the most resilient projects and which warrant the greatest benefits and least impacts from hydropower development in the long term. The findings that larger hydropower projects tend to be associated with higher risk and uncertainty of future losses is reasonable and in accordance with past experience worldwide[31]. Conversely, if smaller dams are prioritized, it should be noted that is critical to understand their cumulative ecological and energy impacts. Once project-specific vulnerabilities are considered, it is important to understand if coordinated dam network operations could minimize losses. For instance, our calculations indicate that if reservoir levels were controlled to maximize system-wide hydropower generation, the increase in generation during the month of minimum generation could be sufficient to offset projected future losses during this critical period (Supplementary Fig. 3).

Considering climate and environmental change for hydropower sustainability

The potential impacts of climate and environmental change that hydropower development is facing in the Tapajós basin represents the uncertain fate of what is occurring in the wider Andes–Amazon as well as other ecologically sensitive tropical regions in Asia and Africa[6,7,32]. A major lesson from past mistakes, summarized by the World Commission on Dams, is that broader social and environmental impacts must be taken into account in hydropower planning[31]. Indeed, recent research in these ecologically sensitive regions with new hydropower development has shifted from local impacts to trade-offs for sustainable regional planning and operations[8,11–13]. As we demonstrated in this paper, the effects of regional environmental change and global climate change could bring non-trivial implications in Brazil's hydropower frontier. While generalizations need to be cautiously made, we argue that the severity of these implications can be similar in other growing economies that see this traditional source of renewable energy as a major mechanism to reach sustainable development goals.

Given the diversity of climate and sociopolitical conditions surrounding the new wave of hydropower, we recommend that further research scaling global/regional change to the watershed/project scale is carried out in the specific regions of development and integrated into the decision-making process in a scientifically sound manner that accounts for uncertainties and trade-offs. Guidelines for how to account for climate uncertainty in individual projects are available[33,34] but how to integrate multiple drivers in a large network of infrastructure projects still remains a challenge in practice. Clearly, considering climate and environmental change in long-term performance is just one aspect related to sustainable hydropower development. Other aspects that need to be further investigated include how dams can be operated to improve riverine ecosystem services[35–37] and how the deployment of other renewables can offset hydropower impacts[12]. Overall, a much broader consideration of development and production effects in local and regional wellbeing is needed to fully understand and promote sustainability, since ensuring the synergy between national and local scales of wellbeing is perhaps the greatest challenge that hydropower faces these days.

Methods

Case-study description. The Tapajós is a large (476,674 km^2) basin in southeastern Amazonia located within the Brazilian states of Amazonas, Rondônia, Pará and Mato Grosso. Elevation in the basin ranges from nearly 800 m in the headwaters in Mato Grosso to less than 10 m at its outlet into the Amazon River (Fig. 1). The Tapajós River itself has a length of nearly 1,880 km and its two largest tributaries, the Juruena and Teles Pires, have lengths of 1,009 and 1,638 km, respectively[38]. Total annual rainfall ranges from 1,274 to 2,624 mm, with generally lower rainfall in the headwaters and greatest in the lower Juruena and upper Tapajós rivers. The mean daily discharge of the Tapajós is 11,833 $m^3 s^{-1}$ (range of 1,440–29,260), making it the fifth largest tributary in terms of flow contribution to the Amazon River[39].

A total of 37 hydropower dams with available feasibility and design information from the inventory of Brazil's National Electricity Agency were included in this study (see detailed data in Supplementary Table 1). The status and priority of these dams are updated annually as part of the 10-yr energy expansion plan performed by Brazil's Energy Research Office. Of the 37 projects studied, four dams in the Teles Pires River are already built or under construction, 13 are at different stages of feasibility studies, and four have been suspended, including the largest project in the basin, the São Luis do Tapajós, with a proposed installed capacity of 8,040 MW. Despite the complicated legal, environmental and cultural challenges that the construction of São Luis do Tapajós could face, we opted to include it in this study because this information could be highly useful if its feasibility is discussed again.

Modelling framework. This study used a series of computer simulation models that allowed us to integrate information on continental environmental change to daily calculations of river hydrology and hydropower operations (see diagram in Supplementary Fig. 1). We used the Ecosystem Demography Model v.2 (ED2) to simulate the effect of global climate change and regional deforestation on the water cycle. ED2 is a terrestrial biosphere model that describes vegetation community dynamics (growth, reproduction and mortality) and accompanying energy, carbon and water fluxes of heterogeneous and functionally diverse plant canopies (different plant sizes and successional groups) as a function of climate, soils and annually changing human disturbance characteristics[40,41]. ED2 has been applied to the Amazon before, demonstrating its ability to represent the sensitivity of ecosystem's structure and function to climate variability[42]. Daily estimates of surface and subsurface runoff from ED2 grid cells were then routed through the landscape using an hydraulic routine that represents runoff as a series of three linear reservoirs of surface flow, intermediate flow and groundwater, ultimately draining into the river network. This allowed us to estimate daily river flows through the basin with evaluated performance and effects of historical climate variability and deforestation[30,43]. Estimated river flows were then used to drive a reservoir and dam hydraulic routing simulation model. To this end, we created a model network of 37 dams and reservoirs using HEC-ResSim, a well-established simulation model developed by the US Army Corps of Engineers for feasibility and planning purposes, with proven performance for large networks of hydropower projects in remote regions[44]. This model allowed us to compute daily water budgets and hydropower generation as a function of inflow river discharge, reservoir spatial configuration, dam outlets design, turbine capacity and seasonal operational policies, which dictate expected reservoir water levels and flow discharge. This approach allowed us to estimate supply-driven potential electricity generation from each hydropower project, which is different from the demand-driven approach more commonly used in electricity distribution operations in Brazil. Because dams in the lower Amazon have little storage and will primarily be used for hydropower (as opposed to multipurpose dams for agricultural, recreational or human consumption), they will be operated as run-of-the-river, with limited ability for water levels to be regulated. This allowed us to simplify operational policies to a single water-level target throughout the year, which could maximize energy at each dam as long as the water flow into the reservoir was greater than the turbine design discharge plus environmental flow requirements. If inflows decreased during the dry season beyond a minimum critical threshold, turbines might need to be shut down, decreasing the overall hydropower potential for a particular dam. On the basis of the number of turbines for each project and their design characteristics (minimum and design flow, hydropower capacity), we assumed that hydropower potential could decrease proportionally to the reduction in flow beyond the minimum flow threshold for each turbine.

Datasets. Meteorological data (atmospheric temperature, specific humidity, downward shortwave/longwave radiation, wind speed, air pressure and precipitation) at 3-h intervals were used to force ED2. For both simulation of baseline conditions (1986–2005) and future climate (2026–2045), we used the 3-h simulation results from the HadGem2-ES Earth System Model developed by the Met Office Hadley Centre (United Kingdom), which is part of the Coupled Model Intercomparison Phase 5 (CMIP5) and has been shown to effectively represent historical climatic conditions in the Amazon[45,46]. As demonstrated by Farinosi et al.[18], HadGem2-ES generates future hydrological conditions for this basin that are representative of intermediate projections among CMIP5 models. Land-use change information was used to drive land transitions annually. Historical land-use changes were prescribed from a global dataset[47] and future conditions were assessed from regional projections under conditions that reflect governance efforts prompted in the past decade to control deforestation in the Amazon[48]. A more detailed description of the datasets used to force ED2 can be found elsewhere[18,30,49,50]. Daily measurements of river discharge in 15 stations were used to construct continuous time series at six key locations to evaluate our river flow estimates and to bias-correct projections for future scenarios. Details on the re-analysis, model evaluation and bias-correction procedures are presented in other recent publications[18,30,43].

Our hydropower network model was built on the basis of a database compiled for this study from the national hydropower inventory at the Brazilian Electricity Regulatory Agency's (ANEEL's) library in Brasilia in November 2014 and updated in February of 2016 on the basis of recent project status updates and information collected in the field. This dataset included 50 different sets of quantitative and qualitative information for each project, with information on their feasibility status and geophysical environment, as well as dam and structural design characteristics. A summary of this dataset is provided in Supplementary Table 1.

Simulation scenarios. Five different scenarios related to global climate and deforestation regional effects on hydrology were described in detail by Farinosi et al.[18]. Projections of river discharge were used as the main driver of change for future hydropower generation in this study. The baseline scenario (BL) represents historical conditions for 1986–2005. Two scenarios exemplified future climate changes for moderate and extreme conditions according to Representative Concentration Pathways (RCPs) for the period 2026–2045: the moderate scenario is represented by RCP 4.5 (blLU_rcp45) and the extreme scenario is represented by a RCP 8.5 (blLU_rcp85). Both blLU_rcp45 and blLU_rcp85 use the 2005 historical land use/land cover from the BL scenario. Direct effects of projected future deforestation on the hydrological cycle were considered by running ED2 with the HadGem2-ES RCP 4.5 and 8.5 climate projections and projections of future land transitions for a moderate governance scenario (GOV) from Soares-Filho et al.[48]. This scenario projects an expansion of the agricultural frontier in the upper Tapajós, in particular along the Teles Pires River in the southeast portion of the basin (see Supplementary Fig. 2). Deforestation projections led to two additional future scenarios, one with moderate climate and moderate deforestation (GOV_rcp45) and one with extreme climate change and moderate deforestation (GOV_rcp85). Even though a 'deforestation-only' scenario was not included in this paper, a comparison of blLU_rcp45 with GOV_rcp45, or blLU_rcp85 with GOV_rcp85, would help in isolating the effects of deforestation.

Optimization scenarios. All five simulation scenarios described above assumed dams are operated as run-of-the-river, aiming to maintain maximum water levels in the reservoir. To evaluate the potential effect of operations in offsetting energy generation losses, parallel simulations were developed in which monthly water levels were varied to maximize annual energy generation for the entire dam network. The optimization simulations were carried out with the Prescriptive Reservoir Model[51]. A comparison of the optimized scenarios to the run-of-the-river scenarios for the minimum month of hydropower production is presented in Supplementary Fig. 3.

Statistical analyses. Pairwise comparisons of simulation results were carried out to assess the statistical significance of future changes projected by the model simulations as compared to the simulation for the baseline historical period. Distributions of results were first assessed for normality using the Shapiro–Wilk's test in combination with visual inspection of density and residual plots. Distributions of daily generation by month ($n=630$) were non-normal, thus the Kolmogorov–Smirnov non-parametric test was used. Results of minimum monthly generation by year ($n=21$) were normally distributed, thus the t-test was used. Results in Fig. 3 indicate the level of statistical significance ($P<0.01$ or $P<0.05$) for those scenarios that were indeed significantly different from the baseline. All statistical analyses were carried out with R statistical and computer software v.3.6.2. Complete sets of the statistical analyses carried out are presented in Supplementary Tables 2 and 3.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

1. *International Energy Outlook 2016* (US Energy Information Administration, 2016).
2. *Hydropower Status Report* 41 (IHA, 2016); http://www.hydropower.org/
3. Grill, G. et al. Mapping the world's free-flowing rivers. *Nature* **569**, 215–221 (2019).
4. Poff, N. L., Olden, J. D., Merritt, D. M. & Pepin, D. M. Homogenization of regional river dynamics by dams and global biodiversity implications. *Proc. Natl Acad. Sci. USA* **104**, 5732–5737 (2007).
5. Anderson, E. P. et al. Understanding rivers and their social relations: a critical step to advance environmental water management. *WIREs Water* **6**, e1381 (2019).
6. Moran, E. F., Lopez, M. C., Moore, N., Müller, N. & Hyndman, D. W. Sustainable hydropower in the 21st century. *Proc. Natl Acad. Sci. USA* **115**, 11891–11898 (2018).
7. Winemiller, K. O. et al. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* **351**, 128–129 (2016).
8. Anderson, E. P. et al. Fragmentation of Andes-to-Amazon connectivity by hydropower dams. *Sci. Adv.* **4**, eaao1642 (2018).
9. Arias, M. E. et al. Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland. *Ecol. Modell.* **272**, 252–263 (2014).
10. Finer, M. & Jenkins, C. N. Proliferation of hydroelectric dams in the Andean Amazon and implications for Andes–Amazon connectivity. *PLoS ONE* **7**, e35126 (2012).
11. Piman, T., Cochrane, T. A. & Arias, M. E. Effect of proposed large dams on water flows and hydropower production in the Sekong, Sesan and Srepok Rivers of the Mekong Basin. *River Res. Appl.* **32**, 2095–2108 (2016).
12. Schmitt, R. J. P., Bizzi, S., Castelletti, A. & Kondolf, G. M. Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong. *Nat. Sustain.* **1**, 96–104 (2018).
13. Ziv, G., Baran, E., Nam, S., Rodriguez-Iturbe, I. & Levin, S. A. Trading-off fish biodiversity, food security, and hydropower in the Mekong river basin. *Proc. Natl Acad. Sci. USA* **109**, 5609–5614 (2012).
14. Strand, J. et al. Spatially explicit valuation of the Brazilian Amazon forest's ecosystem services. *Nat. Sustain.* **1**, 657–664 (2018).
15. Coe, M. T. et al. Deforestation and climate feedbacks threaten the ecological integrity of south–southeastern Amazonia. *Philos. Trans. R. Soc. B* **368**, 20120155 (2013).
16. Davidson, E. A. et al. The Amazon basin in transition. *Nature* **481**, 321–328 (2012).
17. Duffy, P. B., Brando, P., Asner, G. P. & Field, C. B. Projections of future meteorological drought and wet periods in the Amazon. *Proc. Natl Acad. Sci. USA* **112**, 13172–13177 (2015).
18. Farinosi, F. et al. Future climate and land use change impacts on river flows in the Tapajós basin in the Brazilian Amazon. *Earth's Future* **7**, 993–1017 (2019).
19. Sorribas, M. V. et al. Projections of climate change effects on discharge and inundation in the Amazon basin. *Clim. Change* **136**, 555–570 (2016).
20. Zhang, K. et al. The fate of Amazonian ecosystems over the coming century arising from changes in climate, atmospheric CO_2 and land-use. *Glob. Change Biol.* **21**, 2569–2587 (2015).
21. Nobre, C. A. et al. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proc. Natl Acad. Sci. USA* **113**, 10759–10768 (2016).
22. Stickler, C. M. et al. Dependence of hydropower energy generation on forests in the Amazon basin at local and regional scales. *Proc. Natl Acad. Sci. USA* **110**, 9601–9606 (2013).
23. *Energy Resources Potential in the 2050 Horizon* (EPE, 2018); https://go.nature.com/2TiiSvS
24. *Operational Capacity Factor* (Itaipu Bionacional, 2019); https://go.nature.com/2T6VhiV
25. Marengo, J. A. et al. Changes in climate and land use over the Amazon Region: current and future variability and trends. *Frontiers in Earth Science* **6**, 228 (2018).
26. *Outlook and Perspective on Regional Energy Integration* (EPE, 2018); https://go.nature.com/2vomX9U
27. Escobar, H. Drought triggers alarms in Brazil's biggest metropolis. *Science* **347**, 812–812 (2015).
28. Fu, R. et al. Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. *Proc. Natl Acad. Sci. USA* **110**, 18110–18115 (2013).
29. Guimberteau, M. et al. Impacts of future deforestation and climate change on the hydrology of the Amazon basin: a multi-model analysis with a new set of land-cover change scenarios. *Hydrol. Earth Syst. Sci.* **21**, 1455–1475 (2017).
30. Arias, M. E., Lee, E., Farinosi, F., Pereira, F. F. & Moorcroft, P. R. Decoupling the effects of deforestation and climate variability in the Tapajós river basin in the Brazilian Amazon. *Hydrol. Process.* **32**, 1648–1663 (2018).

31. World Commission on Dams *Dams and Development. A New Framework for Decision-Making* (Earthscan Publications, 2000).
32. Kareiva, P. M. Dam choices: analyses for multiple needs. *Proc. Natl Acad. Sci. USA* **109**, 5553–5554 (2012).
33. Ray, P. A. & Brown, C. M. *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework* (World Bank, 2015).
34. *Hydropower Climate Resilience Guide* (IHA, 2019); http://www.hydropower.org/
35. Poff, N. L. & Olden, J. D. Can dams be designed for sustainability? *Science* **358**, 1252–1253 (2017).
36. Sabo, J. L. et al. Designing river flows to improve food security futures in the Lower Mekong Basin. *Science* **358**, eaao1053 (2017).
37. Jager, H. I. & Smith, B. T. Sustainable reservoir operation: can we generate hydropower and preserve ecosystem values? *River Res. Appl.* **24**, 340–352 (2008).
38. *Water Resources Strategic Plan of the Right Margin of the Amazon River* (ANA, 2011).
39. *Freshwater Ecoregions Of the World: Tapajos–Juruena* (WWF/TNC, 2013); http://www.feow.org/ecoregions/details/320
40. Moorcroft, P. R., Hurtt, G. C. & Pacala, S. W. A method for scaling vegetation dynamics: the ecosystem demography model (ED). *Ecol. Monogr.* **71**, 557–586 (2001).
41. Medvigy, D., Wofsy, S. C., Munger, J. W., Hollinger, D. Y. & Moorcroft, P. R. Mechanistic scaling of ecosystem function and dynamics in space and time: Ecosystem Demography model version 2. *J. Geophys. Res.* **114**, G01002 (2009).
42. Levine, N. M. et al. Ecosystem heterogeneity determines the ecological resilience of the Amazon to climate change. *Proc. Natl Acad. Sci. USA* **113**, 793–797 (2016).
43. Pereira, F. F. et al. Technical note: a hydrological routing scheme for the ecosystem demography model (ED2+R) tested in the Tapajós river basin in the Brazilian Amazon. *Hydrol. Earth Syst. Sci.* **21**, 4629 (2017).
44. Piman, T., Cochrane, T. A., Arias, M. E., Green, A. & Dat, N. D. Assessment of flow changes from hydropower development and operations in Sekong, Sesan, and Srepok Rivers of the Mekong Basin. *J. Water Resour. Plann. Manag.* **139**, 723–732 (2012).
45. Good, P., Jones, C., Lowe, J., Betts, R. & Gedney, N. Comparing tropical forest projections from two generations of Hadley Centre Earth System models, HadGEM2-ES and HadCM3LC. *J. Clim.* **26**, 495–511 (2013).
46. Sillmann, J., Kharin, V. V., Zhang, X., Zwiers, F. W. & Bronaugh, D. Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. *J. Geophys. Res.* **118**, 1716–1733 (2013).
47. Hurtt, G. C. et al. The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. *Glob. Change Biol.* **12**, 1208–1229 (2006).
48. Soares-Filho, B. S. et al. Modelling conservation in the Amazon basin. *Nature* **440**, 520–523 (2006).
49. Swann, A. L. S., Longo, M., Knox, R. G., Lee, E. & Moorcroft, P. R. Future deforestation in the Amazon and consequences for South American climate. *Agric. Meteorol.* **214–215**, 12–24 (2015).
50. Longo, M. et al. The biophysics, ecology, and biogeochemistry of functionally diverse, vertically and horizontally heterogeneous ecosystems: the Ecosystem Demography model, version 2.2 – Part 2: Model evaluation for tropical South America. *Geosci. Model Dev.* **12**, 4347–4374 (2019).
51. Carl, B. *HEC-PRM Prescriptive Reservoir Model User's Manual* (US Army Corp of Engineers, 2003); https://www.hec.usace.army.mil/software/hec-resprm/
52. DiMiceli, C. M. et al. *Annual Global Automated MODIS Vegetation Continuous Fields (MOD44B) at 250 m Spatial Resolution for Data Years Beginning Day 65, 2000–2010* Collection 5: Percent Tree Cover (Univ. Maryland, 2011).
53. Lehner, B. & Grill, G. Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. *Hydrol. Process.* **27**, 2171–2186 (2013).
54. Lehner, B., Verdin, K. & Jarvis, A. New global hydrography derived from spaceborne elevation data. *Eos* **89**, 93–94 (2008).

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Author contributions
M.E.A., F.F., P.R.M. and J.B. designed the study. M.E.A. and F.F. collected and compiled the data. F.F., E.L. and M.E.A. designed the experiments and ran computer simulations. M.E.A. and F.F. carried out the data analysis. M.E.A. prepared all figures. M.E.A., F.F., E.L., A.L. and P.R.M. wrote the paper.

Competing interests
The authors declare no competing interests.

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Software and code

Policy information about availability of computer code

Data collection	We used the Ecosystem Demography Model Version 2 (ED2) in order to simulate the effect of global climate change and regional deforestation on the water cycle. ED2 is an individual-based terrestrial biosphere model that describes vegetation dynamics (growth, reproduction, and mortality), and accompanying energy, carbon and water fluxes of heterogeneous and functionally diverse plant canopies as a function of climate, soils, and annually-changing human disturbance characteristics.
Data analysis	we created a model network of 37 dams and reservoirs using HEC-ResSim, a well-established and simulation model developed by the US Army Corps of Engineers for feasibility and planning purposes.

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The HEC-ResSim model with all input and out data will be available from the corresponding author upon reasonable request

October 2018

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Study description	This interdisciplinary study synthesize information from global/regional projections, hydropower development plans, and a series of computer models considering biosphere dynamics, surface hydrology, and reservoir routing. The study aimed at understanding the effects of Amazon's future climate and deforestation on hydropower generation in Brazil.
Research sample	We studied 37 large proposed hydropower dams in the Tapajos river basin in the Brazilian Amazon. These dams account for nearly 50% of the inventoried potential expansion in Brazil.
Sampling strategy	The Tapajos region was selected because it represents the critical sustainability challenges that Brazil and other Amazon countries are facing. This region is an important Amazonian tributary, with large natural parks and indigenous reserves, but it is also the center of agricultural (soy) production and hydropower development. We selected these 37 dams specifically based on the Brazilian classification of large national dams, which are those with a installed capacity of 30 MW or greater.
Data collection	A database compiled for this study from the national hydropower inventory at ANEEL's library in Brasilia in November 2014 and updated it in February of 2016 based on recent project status updates and information collected in the field. All other data were compiled from online databases.
Timing and spatial scale	Baseline (historical) simulations were carried out for 1986-2005. Future projections were made for 2026-2045. All simulations were carried out at daily time steps.
Data exclusions	No data were excluded from the analysis.
Reproducibility	Reproducibility in this study was ensure by using datasets and models that are well recognized in the scientific literature and that are available for future use. For instance, all input metereological data came from the UK's Met Office Hadley Centre and are widely available in their website. Moreover, the hydropower reservoir simulation tool used can be downloaded and used for free by anyone. Apart from that, the experiments carried out were based on computer simulations and can be repeated at any given time.
Randomization	This aspect is not particular to our study as we based most of our analyses in computer simulations. In order to account for variability and uncertainty, however, we did carried out 20-yr long simulations at daily temporal resolution
Blinding	Blinding was not particularly relevant to our study for the same reasons as stated above.

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