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

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Title: 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 fueling 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 days, 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 well-being. 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]. The vast majority 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] responsible for biodiversity, ecological and agricultural productivity, as well as cultural value of these aquatic systems and their floodplains[5]. These tradeoffs 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 epicenters of large-scale hydropower development[6,7]. Several efforts have quantified tradeoffs 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 in order 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 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 significant 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 upcoming 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 sub-region 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 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 (aka., generation capacity factor), which once historical flow seasonality and interannual variability is 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 per year). For reference, Itaipu, Brazil's largest hydropower dam, has an installed capacity of 14,000 MW, mean annual production of approximately 95,000 GWh, and an annual generation capacity factor over 90%[24]. The relatively low generation factor of dams in the Tapajós 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[26], 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 significantly 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 approximately 14 days. Consequently, peak daily generation capacity of dams in this study (approximately 507 GWh) could only be achieved during 93 days of the year, from early March to early June. Future climate change could delay this peak period by 22-29 days. 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 to 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 fulfill 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 changes are not considered in the planning process. This aspect is critical due to the low degree of regional interconnection between Brazil and neighboring countries, which makes energy self-sufficiency essential[27].

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[29], 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[17–19,30,31], and if such projected anomalies are not considered in future water resources and energy planning, Brazil could face even more drastic shortages than what 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% - +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, finding that has already been documented for past and future streamflows in the Tapajós[18,28]. 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 in order to assess the most likely long-term performance of hydropower projects. In the case of the Tapajós, 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 the large magnitude and uncertainty of future losses (Fig. 4). For instance, São Simão Alto (SSA in Fig. 4) could generate on average 53.37 GWh per day assuming historical conditions, but future changes are expected to result in a net loss of 1.13-4.14 GWh per day. 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, respectively, 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 per day are expected for all future scenarios. For the other five dams, the range of change in potential power could be +0.024 GWh per day 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 individual dams' performance could help prioritizing the most resilient projects and 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[32]. 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 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[6,7,33]. 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[32]. Indeed, recent research in these ecologically sensitive regions with new hydropower development have shifted from local impacts to tradeoffs 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 socio-political 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 matter that accounts for uncertainties and tradeoffs. Guidelines for how to account for climate uncertainty in individual projects are available[34,35], 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[36–38], 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[39]. 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. The mean daily discharge of the Tapajós is 11,833 m^3/s (range of 1,440-29,260), making it the fifth largest tributary in terms of flow contribution to the Amazon River[40].

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 detail data in Supplementary Table 1). The status and priority of these dams are updated annually as part of the ten-year energy expansion plan performed by Brazil's Energy Research Office. Of the 37 projects studied, 4 dams in the Teles Pires river are already built or under construction, 13 are at different stages of feasibility studies, and 4 have been suspended, including the largest project in the basin, the São Luis do Tapajós (SLT), with a proposed installed capacity of 8,040 MW. Despite the complicated legal, environmental, and cultural challenges that the construction of SLT could face, we opted to include it in this study because this information could be highly useful if its feasibility is discussed again.

Modeling 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 Version 2 (ED2) to simulate the effect of global climate change and regional deforestation on the water cycle. ED2 is an 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[41,42]. ED2 has been applied to the Amazon before, demonstrating its ability to represent the sensitivity of ecosystem's structure and function to climate variability[43]. Daily estimates of surface and sub-surface runoff from ED2 grid cells where then routed through the landscape using a hydraulic routine that represents run-off 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[28,44]. 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[45]. 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 a *demand-driven* approach more commonly used in electricity distribution operations in Brazil. Because dams in the lower Amazon have little storage and will be 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. Based on 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/long-wave radiation, wind speed, air pressure, and precipitation) at 3-hr intervals were used to force ED2. For both simulation of baseline conditions (1986-2005) and future climate (2026-2045), we used the 3-hr simulation results from the HadGem2-ES Earth System Model developed by UK's Met Office Hadley Centre, which is part of the Coupled Model Intercomparison Phase 5 (CMIP5) and has shown to effectively represent historical climatic conditions in the Amazon[46,47]. 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 change were prescribed from a global dataset[48], 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[49]. A more detailed description of the datasets used to force ED2 can be found elsewhere[18,28,50,51]. Daily measurements of river discharge in 15 stations were used to construct continuous time series at six key locations in order to evaluate our river flow estimates and to bias-correct projections for future scenarios. Details on the reanalysis, model evaluation, and bias-correction procedures are presented in other recent publications[18,28,44].

Our hydropower network model was built based on a database compiled for this study from the national hydropower inventory at ANEEL's library in Brasilia in November 2014 and updated in February of 2016 based on recent project status updates and information collected in the field. This dataset included 50 different sets of quantitative and qualitative information for each project, including information on their feasibility status, geophysical environment, as well as dam and structural design characteristics. A summary of this database 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.[49]. 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 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[52], and 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 version 3.6.2. A complete set of the statistical analyses carried out are presented in Supplementary Tables 2 and 3.

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

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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 MEA 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.

Figure Legends

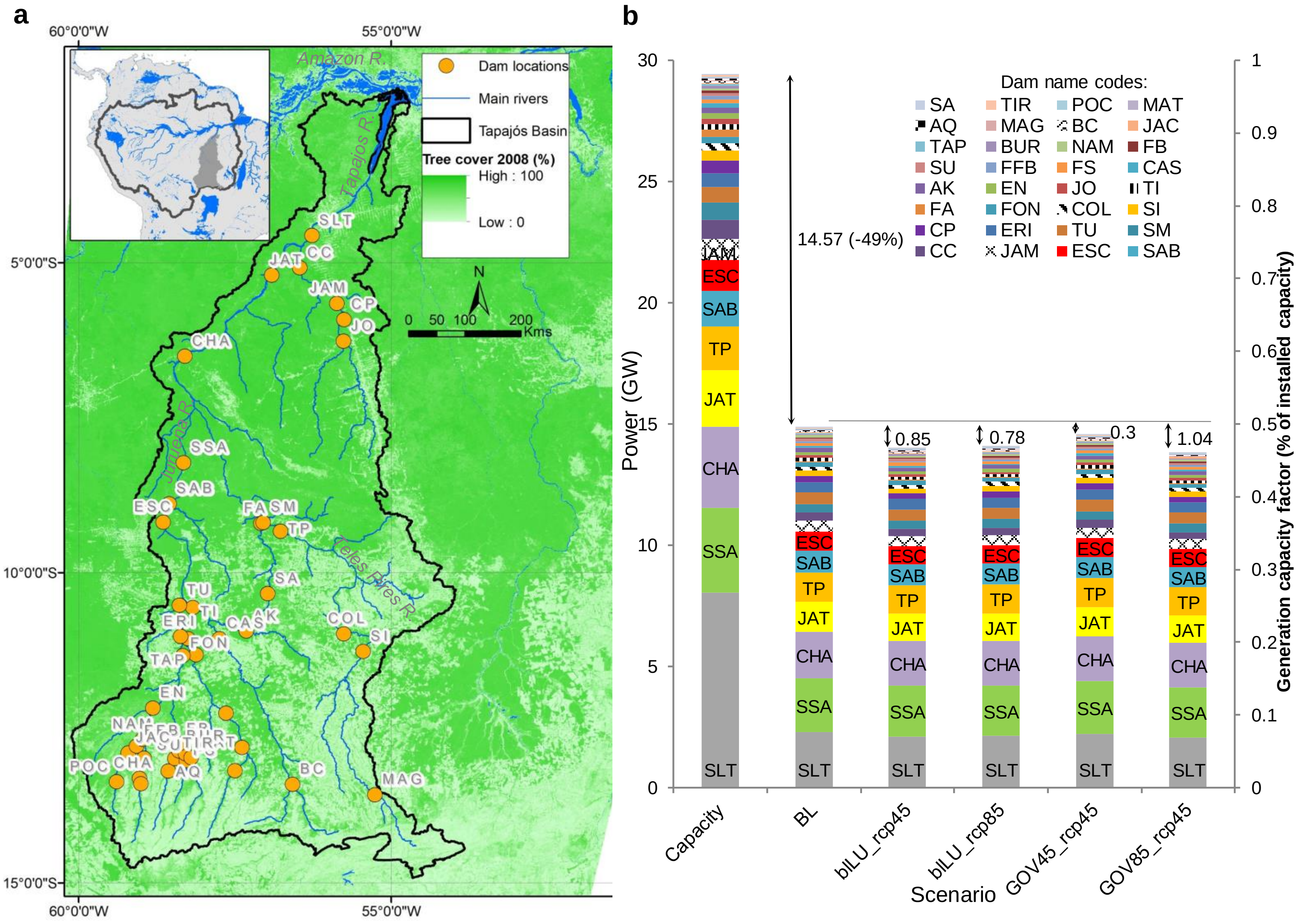
Fig. 1. The inventoried capacity of 37 existing and planned dams in the Tapajós could be 29.4 GW, equivalent to 27% of Brazil's current installed capacity[23]. (**a**) Overview map of study location, with basemap displaying 2008 tree cover as derived from MODIS imagery[25]. (**b**) Proposed cumulative installed capacity compared to potential power for historical hydrological conditions (BL), future scenarios of climate change alone (blLU_rcp45 and blLU_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. Complete dam names are provided in Supplementary Table 1.

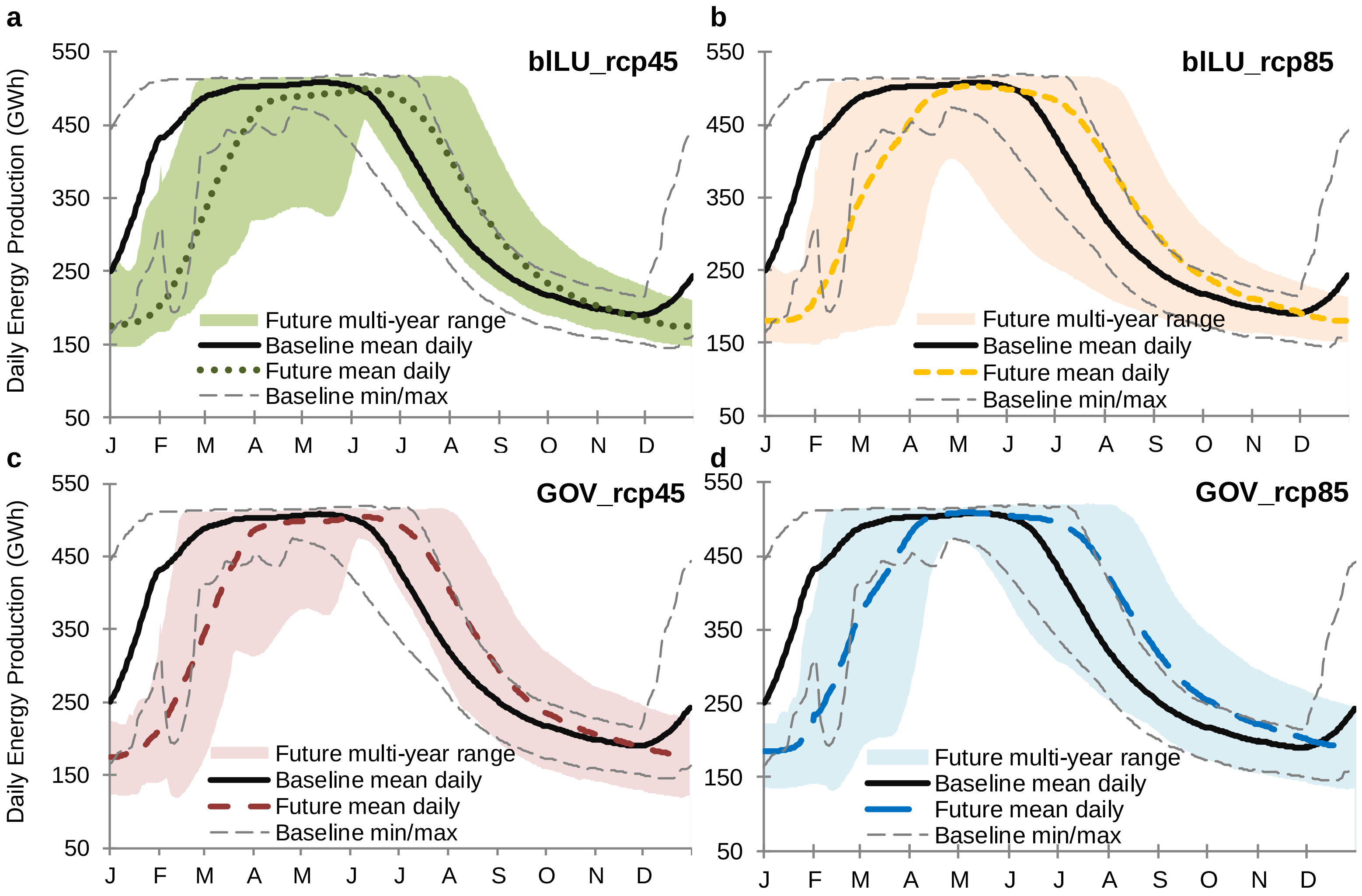
Fig 2. Climate change could drive a 1+ month shift in the seasonal peak of daily electricity generation of dams in the Tapajós basin, which will have implications for Brazil's energy planning. (**a**) and (**b**) represent effects of future climate change. (**c**) and (**d**) represent scenarios of combined future climate change with deforestation. 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.

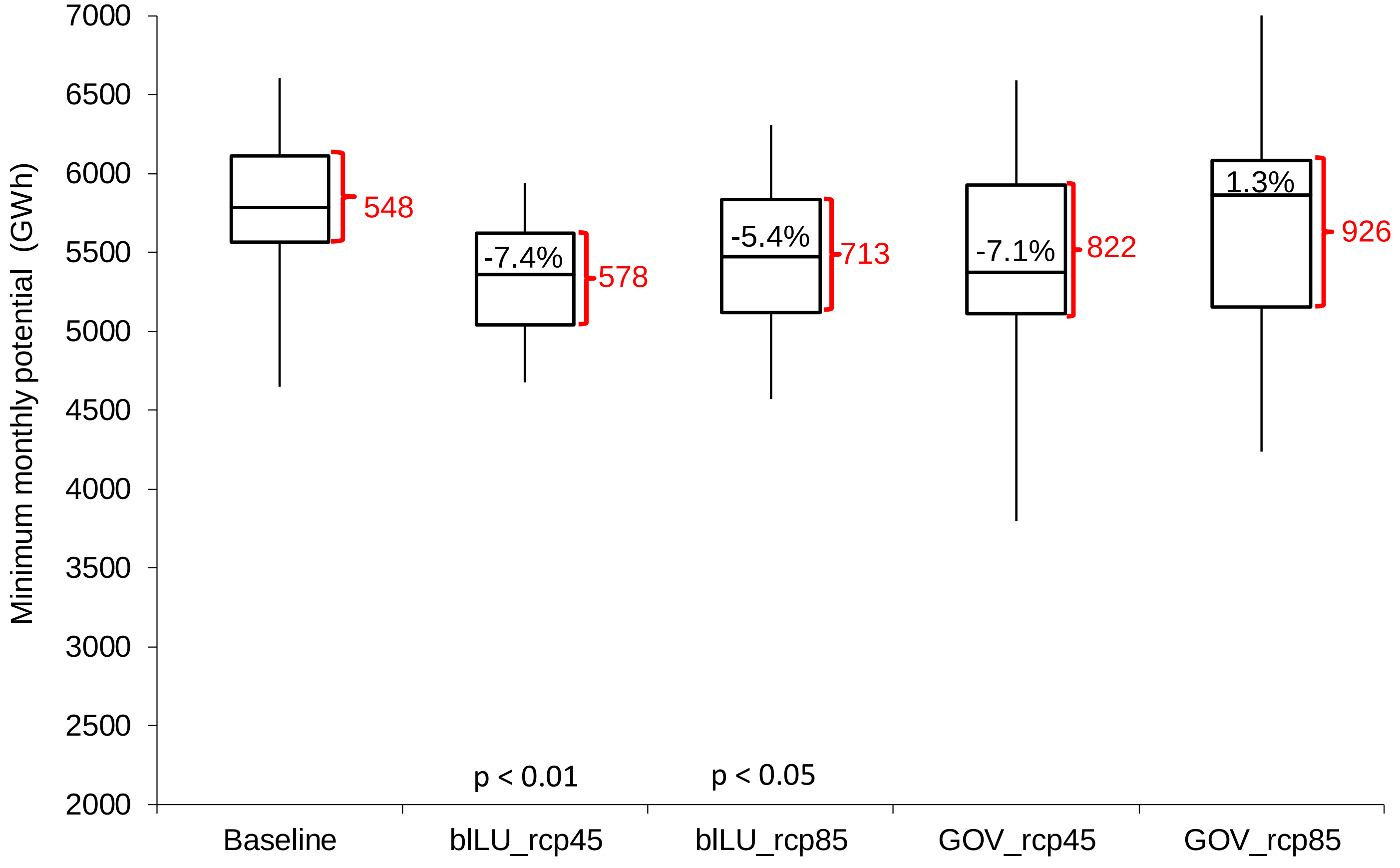
Fig. 3. Electricity generation during the minimum month per year is expected to decrease in magnitude and increase in variability. Numbers in black represent the change in 50th percentile, while numbers in red represent the interquantile range in annual variability (in GWh per month).

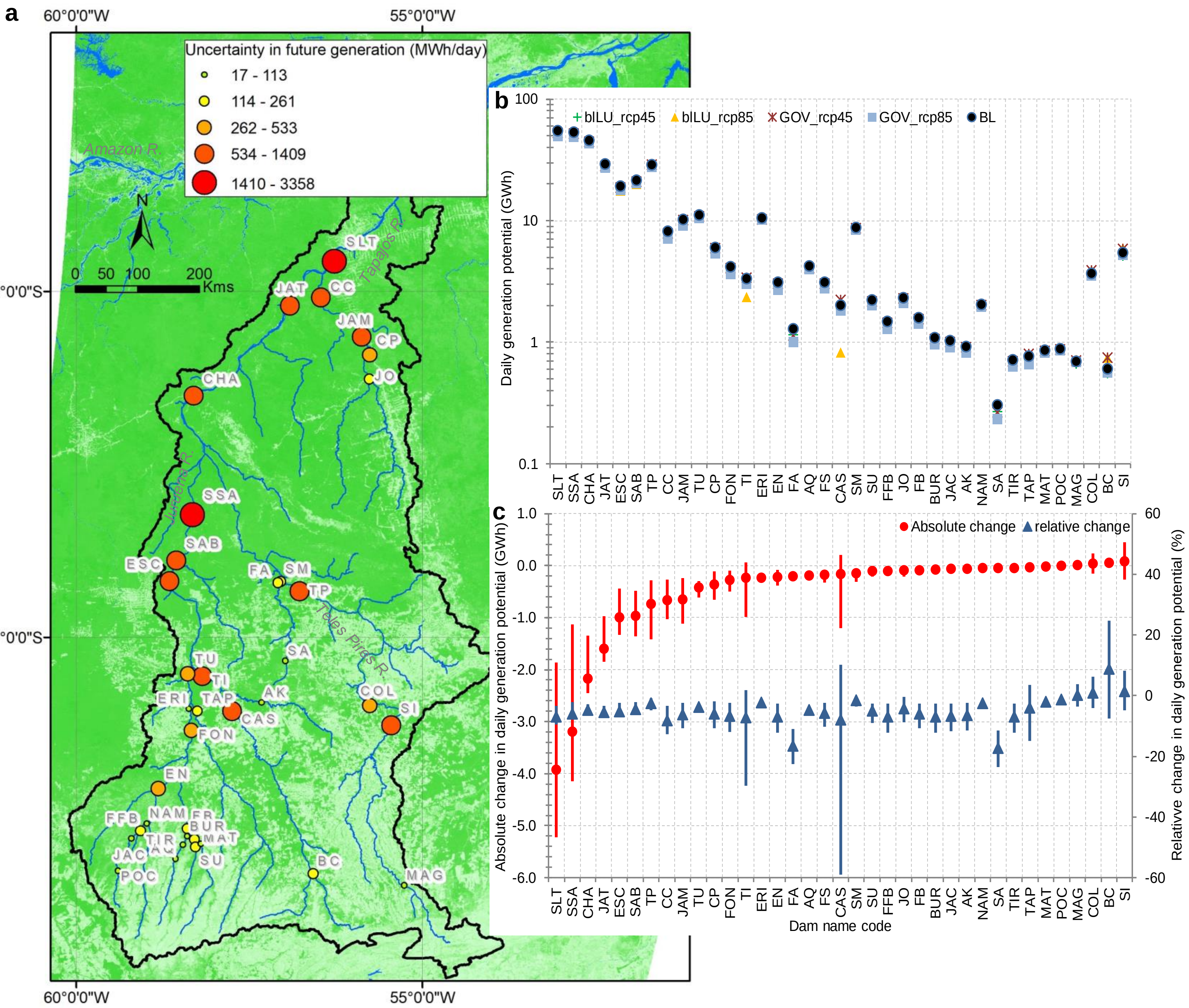
Vertical lines represent the spread of data (n = 21) for each scenario. p-values correspond to the statistical (t-test) comparison between the baseline and the climate change scenarios.

Fig. 4. Understanding the future performance of individual dams can help identify vulnerable projects that may not meet their expected contribution to the national electricity grid. (**a**) Location of dams colored and sized according to uncertainty in future generation change (that is, the difference in mean daily generation between the best and the worst future scenario). (**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). Complete names of dams are provided in Supplementary Table 1.


a
60°0'0"W
55°0'0"W
5°0'0"S
10°0'0"S
15°0'0"S
Amazon R.
Tapajos R.
Juruena R.
Teles Pires R.
Dam locations
Main rivers
Tapajós Basin
Tree cover 2008 (%)
High : 100
Low : 0
N
0 50 100 200 Kms
SLT
CC
JAT
JAM
CP
JO
CHA
SSA
SAB
ESC
FA
SM
TP
SA
TU
TI
ERI
CAS
AK
COL
SI
FON
TAP
EN
NAM
JAC
FFB
BUR
SU
TIR
AQ
POC
CHA
BC
MAG
b
Power (GW)
Generation capacity factor (% of installed capacity)
Scenario
Capacity
BL
bILU_rcp45
bILU_rcp85
GOV45_rcp45
GOV85_rcp45
0
5
10
15
20
25
30
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
14.57 (-49%)
0.85
0.78
0.3
1.04
SLT
SSA
CHA
JAT
TP
SAB
ESC
JAM
Dam name codes:
SA
TIR
POC
MAT
AQ
MAG
BC
JAC
TAP
BUR
NAM
FB
SU
FFB
FS
CAS
AK
EN
JO
TI
FA
FON
COL
SI
CP
ERI
TU
SM
CC
JAM
ESC
SAB


a
b
c
d
bILU_rcp45
bILU_rcp85
GOV_rcp45
GOV_rcp85
Daily Energy Production (GWh)
550
450
350
250
150
50
J
F
M
A
M
J
J
A
S
O
N
D
Future multi-year range
Baseline mean daily
Future mean daily
Baseline min/max


Minimum monthly potential (GWh)
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
548
-7.4%
578
-5.4%
713
-7.1%
822
1.3%
926
p < 0.01
p < 0.05
Baseline
blLU_rcp45
blLU_rcp85
GOV_rcp45
GOV_rcp85


a
60°0'0"W
55°0'0"W
5°0'0"S
10°0'0"S
Uncertainty in future generation (MWh/day)
17 - 113
114 - 261
262 - 533
534 - 1409
1410 - 3358
N
0 50 100 200 Kms
Amazon R.
Tapajós R.
Juruena R.
Teles Pires R.
SLT
CC
JAT
JAM
CP
JO
CHA
SSA
SAB
ESC
FA
SM
TP
SA
TU
TI
ERI
TAP
AK
CAS
FON
COL
SI
EN
FFB
NAM
FB
BUR
MAT
TIR
AQ
JAC
SU
POC
BC
MAG
b
+ blLU_rcp45
▲ blLU_rcp85
✶ GOV_rcp45
■ GOV_rcp85
● BL
Daily generation potential (GWh)
100
10
1
0.1
SLT SSA CHA JAT ESC SAB TP CC JAM TU CP FON TI ERI EN FA AQ FS CAS SM SU FFB JO FB BUR JAC AK NAM SA TIR TAP MAT POC MAG COL BC SI
c
● Absolute change
▲ relative change
Absolute change in daily generation potential (GWh)
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
Relativve change in daily generation potential (%)
60
40
20
0
-20
-40
-60
SLT SSA CHA JAT ESC SAB TP CC JAM TU CP FON TI ERI EN FA AQ FS CAS SM SU FFB JO FB BUR JAC AK NAM SA TIR TAP MAT POC MAG COL BC SI
Dam name code