Dependence of hydropower energy generation on forests in the Amazon Basin at local and regional scales

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Tropical rainforest regions have large hydropower generation potential that figures prominently in many nations' energy growth strategies. Feasibility studies of hydropower plants typically ignore the effect of future deforestation or assume that deforestation will have a positive effect on river discharge and energy generation resulting from declines in evapotranspiration (ET) associated with forest conversion. Forest loss can also reduce river discharge, however, by inhibiting rainfall. We used land use, hydrological, and climate models to examine the local "direct" effects (through changes in ET within the watershed) and the potential regional "indirect" effects (through changes in rainfall) of deforestation on river discharge and energy generation potential for the Belo Monte energy complex, one of the world's largest hydropower plants that is currently under construction on the Xingu River in the eastern Amazon. In the absence of indirect effects of deforestation, simulated deforestation of 20% and 40% within the Xingu River basin increased discharge by 4–8% and 10–12%, with similar increases in energy generation. When indirect effects were considered, deforestation of the Amazon region inhibited rainfall within the Xingu Basin, counterbalancing declines in ET and decreasing discharge by 6–36%. Under business-as-usual projections of forest loss for 2050 (40%), simulated power generation declined to only 25% of maximum plant output and 60% of the industry's own projections. Like other energy sources, hydropower plants present large social and environmental costs. Their reliability as energy sources, however, must take into account their dependence on forests.

climate change | land-use planning | electricity | climate policy | forest policy

Tropical rainforests are globally significant because of their cultural and biological diversity (1), their productivity (2), and their enormous carbon pools (3). The abundant rainfall that has allowed these ecosystems to develop is also associated with large volumes of river water flow and high potential for the generation of electricity through hydropower dams. As a result of this confluence of rainforests and hydropower potential, many nations with large areas of tropical rainforest—including Brazil, Peru, Colombia, the Democratic Republic of the Congo, Vietnam, and Malaysia—plan to expand their hydropower energy capacity over the next 20 y (4, 5).

Hydropower is an attractive energy option for many reasons. It is cheaper than thermoelectric power and most other renewable forms of electricity (6), can provide energy at scale more easily and with fewer disruptions than wind or solar (6), and can potentially provide electrical energy with lower levels of greenhouse gas (GHG) emissions than thermoelectric energy (7), although its effect on methane production could counteract this benefit (8). As with any energy source, hydropower also brings important social and ecological costs. Dam construction and flooding that often accompanies reservoir establishment can negatively affect the lives of local residents including displacement and forced migration (9, 10) and the destruction of community and ancestral lands (11). Hydropower dams disrupt the continuity of river ecosystems and cause the flooding of adjacent riparian and terrestrial ecosystems (12), can result in disease outbreak (9), and can draw large numbers of laborers to remote locations that are left unemployed once the dam is completed (10).

The viability of hydropower projects as reliable sources of electricity has also been a focus of debate, especially in areas where rainfall and river water flow (discharge) are highly seasonal or erratic (3, 13). In this regard, an important aspect of hydropower viability that has received relatively little attention is its dependency on the forests in which dam complexes are embedded. To what extent will future energy production potential of hydropower investments be realized as forests that surround them are cleared?

River discharge is the difference between water input to the watershed (precipitation) and water export via evapotranspiration (ET). Hydropower potential is directly associated with discharge and therefore generally increases when forests are replaced with crops and pastures because forests tend to release more vapor to the atmosphere through ET, leaving less water for discharge (14–16). Forests can also influence hydropower generation indirectly through their effect on regional rainfall patterns. In the Amazon Basin (AB) (17) and in other moist tropical forest regions (18–20), evidence is accumulating—including from observed patterns of rainfall and forest cover (21)—that rainfall systems are maintained, in part, by the forest itself through contribution of water vapor to the atmosphere through ET and through its associated influences on land–atmosphere energy exchange (22–24).

An initial analysis of the interplay between these dual influences of forests on discharge found that projected rates and spatial patterns of future deforestation could significantly diminish water flow in 6 of the 10 major Amazon tributaries (17). The biggest effect of simulated future deforestation on hydrology was found for the Xingu River basin (XB), where discharge is estimated to decline 11–17% below the fully forested scenario. This analysis did not examine the implications of these simulated changes in discharge for hydropower generation, nor did it tease apart the direct (ET within the watershed) versus indirect (precipitation) effects of forests on discharge. These potential indirect effects have not been included in previous studies of hydropower potential, despite growing evidence of the effects of deforestation on rainfall (21)

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and discharge (25) and, thus, have not been considered in energy policy discussions.

In this paper, we present a study of the direct and indirect influences of forests on hydropower generation for the XB. The study examines the Belo Monte hydropower complex (BMHC), which is expected to provide 40% of the additional electricity that Brazil will need by 2019 (26). When completed, BMHC—currently under construction—will be the world's third largest hydropower complex. The project has been under discussion within Brazil and internationally for over 35 y (27). It is controversial because of its predicted impacts on indigenous and nonindigenous communities in the area affected by the dam and its reservoirs (27, 28), because the annual dry season restricts river discharge several months of every year (27), and because of its high economic risk (29). The river's seasonality could be partially addressed through large reservoirs further upriver to retain rainy season water flow to be released during periods of low flow, but this could increase negative impacts on local communities and Amerindian populations as well as the river ecosystem itself and was an important reason previous plant designs were eventually abandoned (28). In its current design, the hydropower complex is implementing a "run-of-the-river" system, in which a portion of the river is diverted into a channel that drops ~90 m alongside of a natural waterfall. This design greatly reduces the size of the reservoir that is needed because it does not depend upon the hydraulic head of a deep, artificial reservoir. This design could potentially have a much diminished impact than the previous design, which projected a total of at least 1,225 km^2 of reservoirs (compared with 441 km^2 currently) (27, 28). The current design does not, however, compensate for the problem of extreme rainfall and river discharge seasonality, which the five reservoirs in the original plan were designed to regulate (27, 28).

We explore three questions: (*i*) How do current and simulated future forest cover at local and regional scales affect the water balance of the XB? (*ii*) How do these forest-dependent changes in XB discharge influence hydroelectric energy generation potential at BMHC? (*iii*) What are the implications of the study results for Brazil's forest, land use, energy, and climate policy? To address these questions, we simulated XB discharge and associated energy generation potential by the BMHC across a range of plausible future forest cover scenarios that allowed us to tease apart the direct and indirect effects of forests on energy generation potential. A range of deforestation scenarios was generated with a land cover simulation model for the XB that provided input to a surface hydrology model, allowing us to assess direct effects of forest cover on discharge. The indirect effects of forest cover were examined using a global climate model with input from AB-wide, simulated land cover scenarios (Fig. 1).

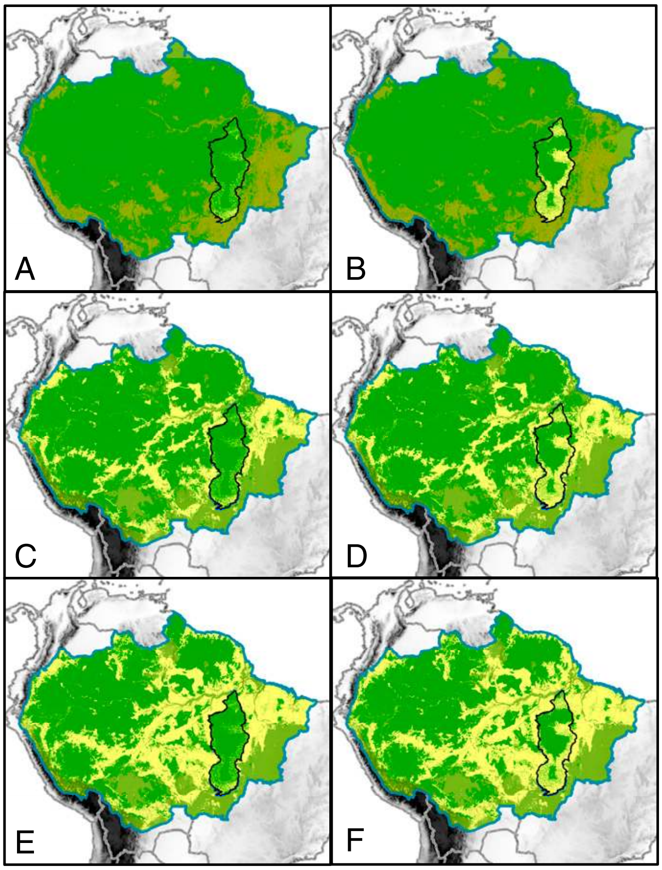

Fig. 1. Vegetation cover of the Xingu Basin (XB) and Amazon Basin (AB) with two land cover classes, tropical evergreen forests and/or cerrado (green) and agriculture (yellow), under six alternative scenarios (percentage deforestation). (*A*) 0% AB and 20% XB: 0% of AB cleared; 20% of XB cleared; (*B*) 0% AB and 40% XB: 0% of AB cleared; 40% of XB cleared; (*C*) 15% AB and 20% XB: 15% of AB cleared; 20% of XB cleared; (*D*) 15% AB and 40% XB: 15% of AB cleared; 40% of XB cleared; (*E*) 40% AB and 20% XB: 40% of AB cleared; 20% of XB cleared; (*F*) 40% AB and 40% XB: 40% of AB cleared; 40% of XB cleared.

Results and Discussion

Annual Water Balance. In the absence of regional, indirect effects of deforestation on climate, simulated local forest clearing in the XB (Fig. 1) caused an increase in discharge, as expected from previous studies (17, 30, 31). XB deforestation of 20% and 40% led to increases in discharge of 4% and 10%, respectively, relative to the fully forested ("reference") scenario (Fig. 2 and Table S1), the result of lower ET of the crops and pastures that replace the forest.

When AB regional indirect effects are included in the simulation, the response is reversed. As regional forest cover declines by 15% and 40%, simulated rainfall within the XB declines, counterbalancing the positive effect on discharge of local XB forest cover (statistical test results in Table S2). Discharge declines by 6–13% under a scenario of 15% (current) regional deforestation, and declines by 30–36% under a scenario of 40% regional deforestation compared with the reference scenario simulation (Fig. 2 and Table S2). These differences in discharge are the result of reductions in rainfall (2,207–5,603 $m^3 \cdot s^{-1}$, 6–15%) that are larger than reductions in ET (801–1,952 $m^3 \cdot s^{-1}$, 3–7%) within the XB.

We also found evidence of an interaction between the effect of forest cover within the XB and AB regional forest cover on the amount of precipitation falling within the basin. Under full regional forest cover, we found no difference in XB rainfall when 20% and 40% of XB forest cover was removed. With a 15% reduction in AB regional forest, the decline in rainfall within the XB was 6% and 7% for 20% and 40% forest cover reductions within the XB, respectively. Under a 40% reduction in regional forest cover, this decline in rainfall was 11% and 15% (Fig. 2).

Water Balance Seasonality. Like many tributaries of the southern Amazon, precipitation and discharge in the XB are highly seasonal, ranging from highs of 59,560 and 20,840 $m^3 \cdot s^{-1}$ and lows of 2,440 and 1,280 $m^3 \cdot s^{-1}$, respectively, over the course of the year (Table S3). Under full forest cover, precipitation in the dry season (June to September) is less than 10% that of the rainy season (October through April). The influence of forest cover on both precipitation and discharge varies depending on the area and scale of deforestation. Under a scenario of 15% regional deforestation, XB precipitation declines 25–48% relative to the reference scenario during August to October (Fig. 3 and Table S2). Under 40% regional deforestation, XB precipitation declines by at least 5% in all months and by 20–43% from July through October. Under both the 15% and 40% regional deforestation scenarios, the decline in XB precipitation is greatest in October. Hence, regional forest clearing prolongs the dry season in the XB.

XB discharge does not track precipitation linearly. Rather, moisture storage within the basin, delays in water reaching the mouth of the river, and differences in ET occurring within the XB

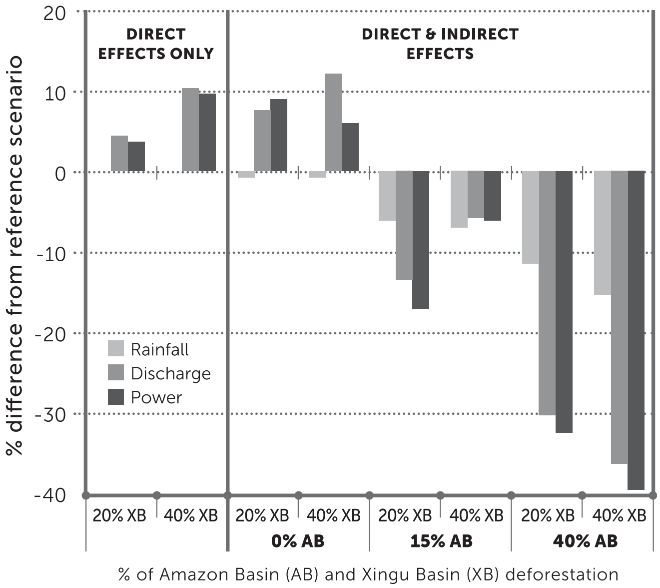

Fig. 2. Percentage difference from reference scenario [0% deforestation within either the Xingu Basin (XB) or Amazon Basin (AB): 0% AB and 0% XB] in mean annual precipitation (Rainfall), discharge (Discharge), and corresponding energy generation potential (Power) under two local deforestation scenarios (20% and 40% deforestation of XB cleared, respectively) and three regional deforestation scenarios (0%, 15%, and 40% of AB cleared, respectively), with and without climate feedbacks. (20% XB: 20% of XB cleared; 40% XB: 40% of XB cleared; 0% AB: 0% of AB cleared; 15% AB: 15% of AB cleared; 40% AB: 40% of AB cleared.)

for each forest cover scenario influence discharge. The absolute declines in simulated discharge are greatest for the 40% regional deforestation scenario during the months of January through June. Discharge from XB is highest in March for the scenario of 40% deforestation in the XB combined with 0% regional (AB) deforestation, and 20% XB deforestation combined with 15% regional deforestation (Fig. 3) and late in the year (November to January) for most deforestation scenarios (Fig. 3 and Table S2). The increase in discharge in the XB deforestation simulations is due to the large decrease in ET that results from forest clearing.

Energy Generation Potential. Because of the river's extreme seasonality and the planned reservoirs' low storage capacity, our discharge projections under current forest and climate conditions indicate that mean annual energy generation potential is likely to achieve only 33–38% of BMHC's maximum installed capacity of 11,000 MW (Fig. 2). According to official project documents, the BMHC's minimum assured average energy generation potential is 4,419 MW, or 40% of installed capacity (32). This calculation includes downward adjustments of estimated installed capacity to account for drought events that could restrict the plant's energy generation and threaten energy delivery throughout the Brazilian grid. These official estimates do not include the effects of future deforestation, however.

The deforestation scenarios we examined could reduce BMHC energy generation by ~38% of the industry's own estimates. If deforestation proceeds as predicted (33) within both the Xingu and Amazon basins and simulated indirect effects of forests on rainfall are taken into consideration, mean annual power generation potential could decline to ~25% of maximum installed capacity (Fig. 2). Monthly power generation potential is likely to fall short of 50% of maximum installed capacity in all but 2 mo under the "business-as-usual" (BAU) scenario and all but 3–5 mo under current conditions (Fig. 4 and Table S4). Current installed hydropower capacity in Brazil is 78,351 MW and accounts for ~80% of electrical energy consumption in the country (34). The potential reduction in output we project for BMHC represents about 3% of Brazil's current installed capacity, and a larger percentage of actual energy output.

Implications for Other Tropical Watersheds. Evidence of rainfall dependence on regional forest cover has been found for the three major tropical forest regions of world (Amazon, Central Africa, Southeast Asia) (18–20, 35, 36). This dependence could affect

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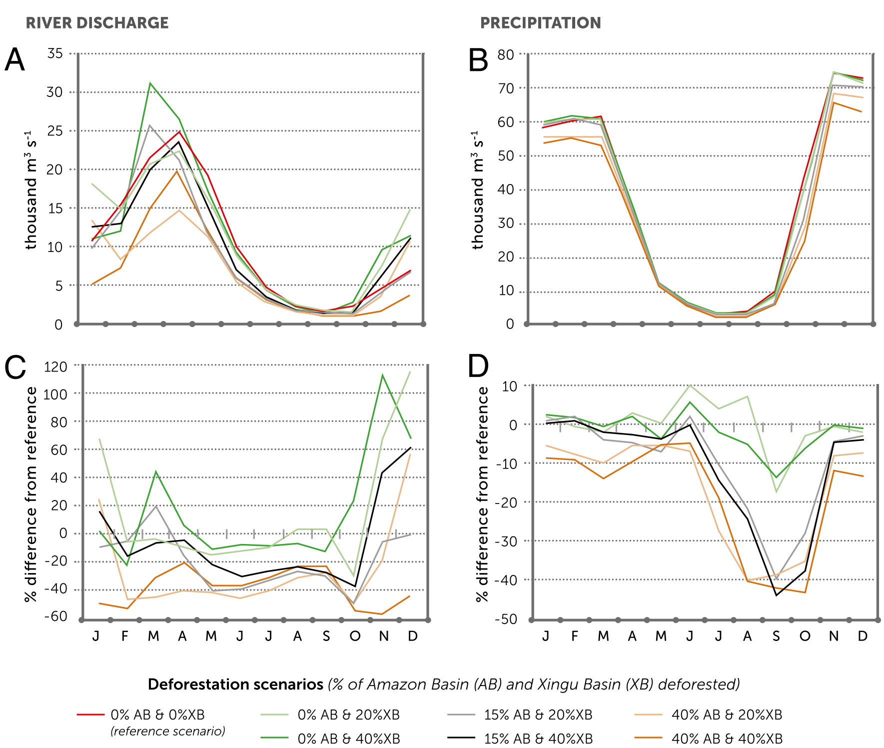

Fig. 3. Difference in monthly discharge from the Xingu River and precipitation summed over the Xingu River basin under alternative scenarios of local [Xingu Basin (XB)] and regional [Amazon Basin (AB)] forest cover, with direct effects and with both direct and indirect effects. Estimated mean monthly (*A*) discharge (in cubic meters per second) and (*B*) precipitation (in cubic meters per second) generated under seven alternative scenarios. Percentage difference in mean monthly (*C*) discharge and (*D*) precipitation from full local and regional forest cover (reference scenario: 0% AB and 0% XB) for six alternative scenarios.

hydropower expansion plans of a large number of developing nations in these regions (4, 5). The potential of regional deforestation to inhibit rainfall sufficiently to constrain energy generation is greatest where rainfall seasonality is already pronounced and where deforestation is expected to be greatest (e.g., where new roads will stimulate forest clearing). For example, in the AB, energy generation potential of hydropower plants under consideration for the Tapajós River may be affected by the paving of the BR-163 highway that runs along it (37), while that of the Rio Madeira may be affected by paving of the BR-319 highway (37, 38). Peruvian hydropower could depend upon deforestation dynamics along the recently paved Interoceanic highway and the intermittently paved BR-364 highway.

Climate Change. Our study examined the influence of deforestation-driven climate change, but it did not examine the influence of climate change driven by the accumulation of heat-trapping gases in the atmosphere on future energy generation, nor did it examine trends in extreme droughts or floods. Most climate models predict higher temperatures and lower rainfall in the southeastern Amazon region, including the headwaters of the Xingu River (35, 39, 40). The net result of the interacting influences of deforestation and increasing CO_2 is likely to be a large increase in surface temperature and a small decrease in precipitation and ET (35, 41), leading to drying and, in particular, a lengthening of the dry season. If extreme droughts such as those that affected the AB in 2005 and 2010 (42, 43) become more common in a warming world, the minimum assured energy generation of existing and planned hydropower plants could decline even if full regional forest cover is maintained. Other tropical regions are likely to be more severely affected than the AB, whose climate is less sensitive to forest removal due to the role of the Andes mountain range in encouraging precipitation (26).

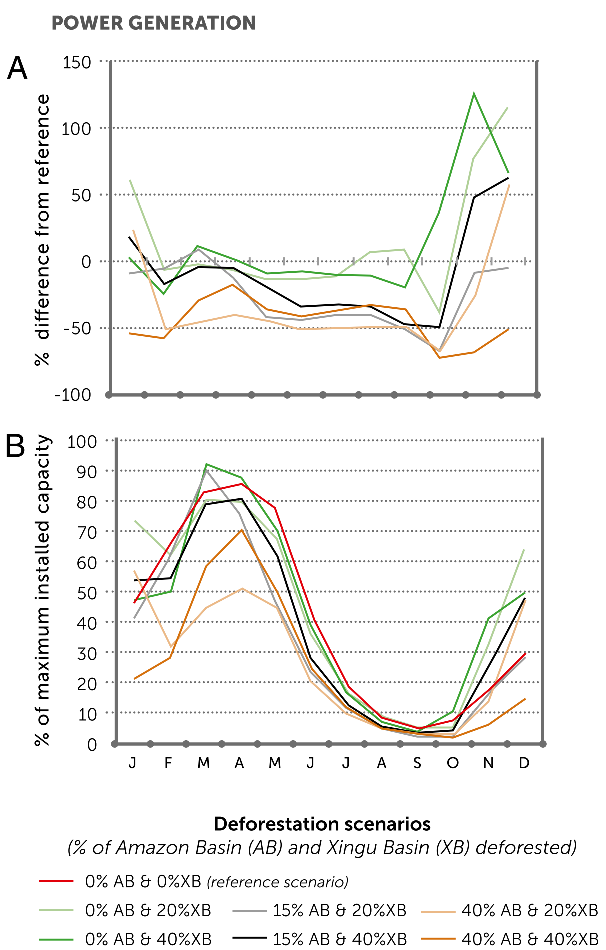

Fig. 4. Difference in monthly power generation potential at the Belo Monte power plant on the Xingu River under alternative scenarios of local [Xingu Basin (XB)] and regional [Amazon Basin (AB)] forest cover, with climate feedbacks. (*A*) The percentage difference from reference scenario (0% AB and 0% XB) in mean monthly energy generation potential under six alternative scenarios. (*B*) Mean monthly power generation potential as a percentage of maximum installed capacity (11,000 MW) under seven alternative scenarios.

Energy Pathways. Nations must decide how to meet growing needs for electrical energy while minimizing GHG emissions and other social and environmental costs. In the near- to medium-term, hydroelectric power is an important option for achieving the former. Hydropower's GHG emissions factor (4–18 g CO_2 equivalent per kWh) is 36–167 times lower than the emissions from thermoelectric power (5, 44). Compared with other renewables, on a lifecycle basis, hydropower releases fewer GHG emissions than electricity generation from biomass and solar and about the same as emissions from wind, nuclear, and geothermal plants. Hydropower's GHG emission efficiency declines when methane outgassing from reservoirs and associated structures (7, 8, 45, 46) is included in the calculation, although the size of this effect is disputed (47). As technological advances for solar and wind energy improve their competitiveness, a major obstacle to the transition to renewable energy is storing excess electricity for times when low river discharge, low wind, and low sunlight restrict electricity generation. Currently, however, Brazil's discovery and development of a massive deep-water petroleum reserve may provoke a reevaluation of this nation's energy policy (48).

Trade-offs and Policy Implications. Integrated approaches to energy, transportation infrastructure, and land use planning and policy are needed to optimize societal gains and minimize costs of hydropower plants and other major infrastructure investments in tropical rainforest regions. These approaches must address plausible scenarios of future climatic and economic conditions; highways, other infrastructure, and land uses should be planned to secure rainfall systems that may depend upon regional forest cover so as to avoid or postpone a cycle of drought and forest fire that could lead to a regional forest dieback (49). Scenarios of possible future changes in rainfall and ET that could occur through the influence of deforestation and the accumulation of GHGs in the atmosphere should be routinely included in hydropower viability assessments, prioritizing output from carefully validated climate, hydrology, and land use models, such as those used in this study. One of the best ways of reducing the risk of regional rainfall inhibition in the AB region and its negative effects on hydropower generation, agricultural systems, and forest fire may be to slow and eventually end deforestation and reestablish forest cover on the large areas of degraded cattle pasture along the eastern fringe of the AB forest (49). The rate of deforestation has declined by 76% in the last 6 y (50, 51), although rising commodity prices could help to reverse this trend. In this regard, nascent policy frameworks focused on lowering deforestation rates, including Brazil's National Climate Change Policy, and Reducing Emissions from Deforestation and Forest Degradation (REDD+) initiatives, represent important opportunities to create incentives to continue lowering deforestation while reestablishing forests on cleared land (50). Political support for such initiatives might increase if the powerful electricity sector regarded the maintenance of forest cover in the AB and elsewhere as a mechanism for securing future hydropower generation, fostering a synergistic link between energy and forest policies designed to lower GHG emissions.

The construction and maintenance of BMHC and other hydropower projects present substantial social and environmental costs, particularly for the poorest or weakest members of society. However, the BMHC project also shows that an increasingly stringent licensing process and an engaged civil society can broaden the discussion of risks and benefits (27) and lead to major redesign of an enormous infrastructure project (28). Despite the project redesign, key stretches of the river will be altered, affecting local communities and aquatic ecosystems. Furthermore, the construction itself is leading to local deforestation (52), skyrocketing land prices in and around Altamira, and rapid population growth, placing burdens on local health, education, and sanitation services (53). Such growth brings with it the potential of increasing social instability (e.g., crime, income disparity). The results of this analysis indicate that further debate is needed on the viability of BMHC. The hydropower construction industry and state and federal governments have considerable room to improve practice, governance, and analysis related to hydropower installations. They should have plans and programs in place to (*i*) address the negative impacts associated with the implantation of hydropower complexes, including the additional pressure on local government services and public security, (*ii*) efficiently and equitably address the needs of affected groups, (*iii*) ensure that potential benefits the hydropower complex can generate for the regional population in terms of employment, increased demand for local products, and abundant energy are maximized, and (*iv*) include climate change and rainfall dependence on forests in viability assessments.

Conclusion

Considerable controversy around the BMHC has focused on its social and ecological impacts, with some attention paid as well to the extreme seasonality of rainfall in the XB that lowers power generation capacity. Our analyses provide evidence that the viability of this and other hydropower projects must also be examined in light of the effects of regional changes in forest cover on rainfall. In its original design, the major mechanism for increasing BMHC dry season energy generation was to create a series of large upriver dams and reservoirs. Although the attempt to minimize impacts by using a run-of-the river design may be politically and environmentally sensible, it may not be the most appropriate model for rivers with such highly seasonal patterns of discharge from an energy production and financial perspective. It is this trade-off in combination with the hydroelectric sector's variable track record within Brazil that may cause the most skepticism on the part of groups concerned about BMHC's social and environmental impacts now and in the future.

As tropical rainforest nations turn increasingly to hydropower to meet growing demands for "green" electricity, it is important that the relationship between forest cover and river discharge is incorporated into viability assessments. As has long been understood, forest clearing within a watershed can increase discharge by lowering ET. However, regional forest clearing outside the basin can potentially reduce discharge and energy generation significantly by inhibiting rainfall. In addition to the direct social and ecological impacts of hydropower plants in rainforest regions, regional planning and policy processes should also take into consideration the linkages between energy, transportation infrastructure, land use systems, and interactions among the three. Integrated planning and policy approaches will become increasingly important as the escalating global and regional demands for new agricultural land, minerals, water, and energy shift to tropical forest regions where much of the potential for expanding land-based production and energy is found.

Methods

Experimental Design. An important feature of this study is that we are able to simulate discharge in the XB using coupled and uncoupled terrestrial ecosystem and climate models developed for the AB region (17). These models are fed with output from spatially explicit simulations of future land use provided by models designed to represent the effects of Brazilian land use policies (33, 54). The 40% deforestation level for the entire Amazon and Xingu basins was used as a plausible BAU scenario for 2050 (33). This scenario is conservative in that it omits regional forest "dieback" (through logging and fire) that can reduce ET. Recent policy interventions that have reduced deforestation in the AB region illustrate the potential to avoid deforestation-driven reductions in hydropower generation.

We made two sets of simulations: (*i*) one with a land surface model [Integrated Biosphere Simulator (IBIS) terrestrial ecosystem model] that does not consider feedbacks between land cover change and climate, and (*ii*) one with a fully coupled atmospheric general circulation and land surface model [Community Climate Model (CCM3)/IBIS] (17).

Simulations with direct effects only. In one set of simulations, IBIS was forced with prescribed identical climate and vegetation representing three spatially simulated land cover scenarios for the XB: 0%, 20%, and 40% deforestation. The scenarios correspond to no forest clearing, implementation of forest protection policies ("governance"), and continuation of historical deforestation trends to 2050 (BAU). The landscapes were generated by a high-resolution dynamic landscape simulation model adapted from ref. 54.

Simulations with direct and indirect effects. A second series of seven simulations were made with a global climate model (CCM3) coupled to the IBIS land surface model. For this series, two of the XB land cover scenarios described above (20% and 40% deforestation) were integrated into each of three AB land cover scenarios (0%, 15%, 40%), representing no deforestation, current (2000) clearing (55), and continuation of historical deforestation trends to 2050 (33). We generated a "reference scenario" representing the landscape with no significant clearing of native vegetation in either the XB or the rest of the AB. For all simulated landscapes, percentage of clearing was calculated after scenario assumptions were applied and landscape change simulations were carried out for the specified number of years.

Uncertainty. The vegetation (IBIS), hydrology (Terrestrial Hydrology Model with Biogeochemistry; THMB), and climate (CCM3) models used in this study have been extensively calibrated and validated for the AB (17). Rainfall inhibition simulated in this study may be conservative, as CCM3 simulates rainfall that is 7.6% higher than rainfall measured at stations in the core region of AB and 3.2% higher than measurements in the arc of deforestation (56). In general, however, global climate models, such as CCM3, indicate greater effects of deforestation on rainfall than mesoscale models (such as Regional Atmospheric Modeling System) (20). Error associated with simulations of ET and runoff (IBIS) were minimized by calculating a correction factor between discharge estimated by IBIS and that estimated by BMHC project engineers using the same measured climate data (*SI Text S1*). THMB uses a mass balance approach to estimate discharge and has a small error associated with the timing of discharge, but is otherwise tied to rainfall and ET estimates. Despite the care with which the models used in this study were calibrated, we did not eliminate the possibility of model bias. Further research with multiple models is necessary to confirm these results. Nevertheless, the general trends projected by the models we use are consistent with other simulations (40) and observations (21) in suggesting that large-scale deforestation will lead to reduced rainfall and, ultimately, reduced river flow.

The land cover simulations (based on refs. 33 and 54) are used to provide an envelope of plausible future deforestation scenarios with a realistic spatial distribution calibrated with measured deforestation patterns in response to existing and planned infrastructure development in the region (33). We cannot validate predictions of deforestation trajectories as they are based on scenario-specific assumptions. Nevertheless, the land cover change model we use is the most realistic regarding historical patterns and the only one of these models that is thoroughly validated (57). Furthermore, it is consistent with the projections of other models that project deforestation rates and distribution in response to infrastructure development (58).

Water Balance. We obtained estimates of discharge for both sets of simulations using the THMB terrestrial hydrology model (17). For each simulation, we extracted monthly discharge values for 33 y (1968–2000) for the location near the town of Altamira at which the Brazilian National Water Agency's official river gauge is located (17). For the simulations with direct effects only, precipitation was derived for the same location from an interpolation of observed climate data over the same time period over which the discharge simulations were carried out. For the simulations including direct and indirect effects, precipitation is simulated as a function of land cover change throughout the region.

Energy Generation Potential. For each scenario, we calculated energy generation potential based on the simulated discharge at the Altamira gauge. We only calculated the power generated by the main dam and plant, Belo Monte, not the auxiliary plant and dam (Pimentel) because the former is responsible for 98% of the complex's power generation capacity. The maximum power value after calibration was established at 11,000 MW—the maximum installed capacity of the Belo Monte plant alone. We calibrated the simulated mean monthly discharge for each scenario to data used by project engineers to calculate projected minimum energy production (*SI Text S1* and Table S3). We calibrated simulated discharge with the official

SUSTAINABILITY SCIENCE

observed mean annual discharge used by project engineers, and then reduced the simulated discharge by the amount of flow intended to remain in the river in each month (*SI Text S1*), as dictated by Brazilian legislation (59). Using this reduced flow, we estimated the energy generation potential under each scenario using the following equation:

$$P_m = \Delta h \times Q_m \times g \times EF \times C_{AE} \,,$$

where P_m is mean monthly hydropower potential (in megawatts); Δh is difference in head, 87.5 m (32); Q_m is adjusted mean monthly discharge (in cubic meters per second); g is the force of gravity, 9.81 m•s^{-2}; EF is the efficiency factor given for the turbines and generators (0.918) (32); and C_{AE} is an additional calibration factor (0.92) (*SI Text S1*). C_{AE} calibrates the power generation potential to the assured mean annual energy output cited in project documents (4,419 MW), permitting us to compare our results directly to those reported in official project documents, as official power plant production values are calculated as a function of the contribution to Brazil's national grid and require modeling of the entire grid.

We compared monthly and annual mean discharge, precipitation, and power (n = 33) for each scenario using ANOVA tests (*SI Text S2*).

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