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Future Climate and Land Use Change Impacts on River Flows in the Tapajós Basin in the Brazilian Amazon

Fabio Farinosi[1,2,3], Mauricio E. Arias[1,4], Eunjee Lee[1,5,6], Marcos Longo[7,8], Fabio F. Pereira[1,9], Angela Livino[1,10], Paul R. Moorcroft[1,8], and John Briscoe[1,11]

[1]Sustainability Science Program, Kennedy School of Government, Harvard University, Cambridge, MA, USA, [2]Department of Economics, Ca' Foscari University of Venice, Venice, Italy, [3]Now at European Commission, Joint Research Centre (JRC), Ispra, Italy, [4]Department of Civil and Environmental Engineering, University of South Florida, Tampa, FL, USA, [5]Now at Goddard Earth Sciences Technology and Research, Universities Space Research Association, Columbia, MD, USA, [6]Now at Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, MD, USA, [7]Now at Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [8]Faculty of Arts and Sciences, Harvard University, Cambridge, MA, USA, [9]Now at Department of Energy Engineering, Federal University of Alagoas, Maceió, Brazil, [10]Now at EPE, Empresa de Pesquisa Energética, Rio de Janeiro, Brazil, [11]Deceased 12 November 2014

Key Points:
- Biosphere model simulations of future climate and land use change in southeastern Amazon allow to study the impact of local, regional, and global environmental changes on the basin's surface water hydrology
- Climate change is predicted to reduce river flows, delaying the rainy season and increasing variability
- Land use change is expected to partially offset climate change impact on river flows in the short term

Supporting Information:
- Supporting Information S1

Correspondence to:
F. Farinosi,
fabio.farinosi@gmail.com

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Abstract Land conversion and changing climate are expected to significantly alter tropical forest hydrology. We used a land surface model integrated with a river routing scheme to analyze the hydrological alterations expected in the Tapajós River basin, a large portion of the Brazilian Amazon, caused by two environmental drivers: climate and land use. The model was forced with two future climate scenarios (years 2026–2045) from the Earth System Model HadGem2-ES with moderate (+4.5 W/m^2 radiative forcing value in the year 2100 with respect to preindustrial levels) and severe (+8.5 W/m^2) representative atmospheric carbon dioxide pathways (Representative Concentration Pathways). We tested the sensitivity of our results to the uncertainty in future climate projections by running simulations with IPSL-CM5 (wettest scenarios) and GISS-E2 (driest scenarios). Human land use effects on vegetation were evaluated using a limited and an extreme deforestation scenario. Our analysis indicates that climate change is predicted to reduce river flows across seasons (up to 20%) and bring a considerable shift in flow seasonality toward a later onset (nearly 1.5 months) and increase in interannual variability. While land use change partially counteracts the climate-driven diminishing trend in river flows, it is expected to contribute to a further increase in interannual and intraannual variability. From a water management perspective, the overall reduction of river flows and their increased variability, combined with the shift and the shortening of the wet season, could potentially affect the productivity of the large hydropower systems planned for the region and the growing demand for agricultural and transport expansion.

Plain Language Summary Climate and land use change are expected to heavily modify the water cycle. This is particularly true in tropical areas, where human-driven changes may completely alter river discharge. The Amazon is the largest of the remaining tropical forests. Increasing agriculture and livestock production have significantly altered land cover in the region. This pattern is projected to continue in the coming decades. The change in the Amazon's future is highly uncertain: the direct effects of climate and land use change are not well understood and the response also depends on complex Earth-atmosphere exchanges. We used computer models representing water and energy cycles over time to understand how environmental changes are likely to alter the discharge of the Tapajós River system in southeastern Amazon. By combining two climate and two land use scenarios, we found that climate change is expected to reduce the river flows in the basin, bringing a delay in the flow seasonality and increasing the overall variability. Land use change, conversely, is expected to cause an increase in flow magnitude and variability. Besides the serious environmental consequences, these findings have important implications for the management and development of water in this strategic area for Brazil's energy and food production.

1. Introduction

Tropical forested river basins have been subject to increasing human pressure over the past several decades. Most of them lie in developing countries where economic development is boosting demand for increased exploitation of the natural resources (wood, land for agriculture, water, and minerals) they can provide.

Consequently, many tropical river basins have been heavily deforested, with primary vegetation being replaced by agricultural land (Lewis et al., 2015). Moreover, climate change is expected to further impact the ecological functioning of tropical forests (Millar & Stephenson, 2015; Trumbore et al., 2015). Increasing temperature and moisture stress are expected to heavily affect tropical forest productivity (Schiermeier, 2009), with increasing risk of activating negative feedbacks between the biosphere and the atmosphere (Cox et al., 2004).

The Amazon is the largest of the remaining tropical forests; however, increasing economic activities in the area, such as agriculture and livestock production, have significantly altered land cover in the region. For instance, Lemos and de Silva (2011) estimated that about 16% of the 4.2×10^6 km^2 of forest in the Brazilian Amazon was lost in the period 1970–2009. The majority of this forest loss occurred between 1990 and 2005, the period of major expansion of agriculture in the Brazilian states of Mato Grosso, Rondonia, and Pará (Aragão et al., 2014; Lapola et al., 2013; Davidson et al., 2012; Lemos & de Silva, 2011; Soares-Filho et al., 2006;). In the first decade of the 21st century, the Brazilian government implemented actions to minimize the deforestation rates through new regulations and monitoring strategies (Lapola et al., 2013; Nepstad et al., 2014), which have been effective, substantially reducing the rate of deforestation in the past decade. However, the demand for land and natural resources in the Amazon area remains high and deforestation rates increased again after 2014 (Marengo et al., 2018), as governance measures were not maintained (Lapola et al., 2013; Rochedo et al., 2018). Brazil is among the top world producers of soybean, corn, and cattle, with substantially low efficiency in terms of production per unit of area (Battisti et al., 2018; Cohn et al., 2014; FAO n.d.). The combination of deforestation and agricultural expansion has several consequences for the hydrological cycle, in particular by decreasing evapotranspiration and increasing surface runoff (Andréassian, 2004; Arias et al., 2018; Dias et al., 2015).

The future extent and composition of the Amazon forest will be determined by decisions made both at local scales, in terms of land use and development of the area, and at global scales, in terms of climate change mitigation (*Aragão* et al., 2018 *and* 2014; Kruijt et al., 2014; Lapola et al., 2013; Marengo et al., 2018; Nepstad et al., 2014; Sampaio et al., 2018; Soares-Filho et al., 2006). Overall, the level of uncertainty with the Amazon's future is high: the direct effects of climate and land use change on tropical forest ecosystems are not well understood, and in addition, the net response also depends on complex biosphere-atmosphere feedback mechanisms between the ecosystem and the region's climate (e.g., Aragão et al., 2014; Cox et al., 2004; Swann et al., 2015; Zhang et al., 2015).

Changes in land use, land cover, and climate all threaten the environmental integrity of the broader Amazon (Aragão et al., 2014; Barlow et al., 2016; Marengo et al., 2018) and with this the water cycle of the region (Nobre et al., 2016). The combined effects of agricultural expansion, forest degradation, and climate change are expected to affect the region's hydrology and impact water-related sectors (Malhi et al., 2008). Some of the potential effects include reducing water available for human consumption; disrupting river navigation and hydropower generation; increasing frequency and magnitude of extreme hydrological events such as floods and dry spells; augmenting forest fragmentation, drought frequency, and altering fire frequency; and decreasing the overall agricultural and economic productivity (Aragão et al., 2018; Coe et al., 2013; Davidson et al., 2012; Marengo et al., 2018). Among these, hydropower is of great importance because Brazil, with approximately 100 GW of installed capacity, has the world's third largest hydropower installed capacity after China and the United States (China 341 GW, United States 103 GW, and Brazil 100 GW (IHA, 2018)) (US EIA, 2018; IHA, 2018; MME & EPE, 2017a; IEA, 2013; REN21, 2013): as of 2016, approximately 64% of the almost 151 GW of generation capacity in the country is represented by hydropower. In the same year, electricity generated by these plants accounted for about 66% of the total energy produced (~377 of ~568 TWh; US EIA, 2018; MME & EPE, 2017a). According to the 2024 Ten-Year Development Plan developed by the Brazilian Government, the hydropower installed capacity was expected to increase from 85 to 119 GW (about 40%) between 2014 and 2024, most of which was planned in the Amazon (MME & EPE, 2015). The most recent 2026 Ten-Year Development Plan reduced the projected installations to about 110 GW in order to account for the general slowdown of the country's economic growth but confirmed the installation of new hydropower plants in the Amazon area (MME & EPE, 2017b). The strong linkages between the hydrological cycle of tropical rivers and forests imply that deforestation is likely to affect hydropower production. Stickler et al. (2013) found that deforesting 20% or 40% of the upstream portion of the Xingu River Basin would result in an increase in runoff and consequently hydropower production of the

Belo Monte Complex by 4–8% and 10–12%, respectively. This direct effect, however, is likely to be offset by the indirect effects of deforestation due to decrease of evapotranspiration and precipitation. Adding the indirect effect, the two levels of deforestation would result in a decrease of discharge and hydropower production of about 6% to 36% (Stickler et al., 2013). Similar results were found for the Tocantins basin (Von Randow et al., 2019).

This study focuses on the Tapajós River basin, the fifth largest tributary to the Amazon River, where major water development plans could be affected by its complex landforms and hydrology. The basin is characterized by intense agricultural activities concentrated in its southern portion in the State of Mato Grosso. Moreover, the Tapajós basin is home to one of the most ambitious hydropower development plans in South America: a system of more than 40 large and medium dams is planned for this basin, representing one of the largest portions (about 20% of the installed capacity—almost 50% if considering the 2024 Ten-Year Development Plan) of the planned Brazilian future investments in electricity production (MME & EPE, 2015). Although more recently the investments in the installation of new capacity in the area were slowed down, the recent political debate brought again to the center of the discussion the exploitation of the Amazon natural resources (Artaxo, 2019; Nature Editorials, 2018; Tollefson, 2018).

In this paper, we aim to understand how anthropogenic disturbances in climate and land cover dynamics are expected to impact the river flows in the Tapajós River basin in the next few decades. We analyze this issue by conducting a series of simulations with different combinations of climate and land use change scenarios using the Ecosystem Demography version 2 (ED2; Longo et al., 2019; Longo et al., 2019; Medvigy et al., 2009) land surface model coupled with a flow routing simulation model (ED2+R; Pereira et al., 2017). The use of land surface models able to capture ecosystem dynamics, such as ED2, is crucial to understanding the implications of land cover change for the main variables representing the water cycle (Knox et al., 2015); hence, these models are increasingly being used for computing hydrological fluxes at large scales (Zulkafli et al., 2013). Land surface models are able to reproduce the modification of the vertical water balance within climatological grid cells over time, including water uptake by different plant functional types found within the ecosystem and the resulting dynamics of evapotranspiration, soil moisture, percolation, and surface and subsurface runoff. Their main advantage is the ability to represent the suite of interlinked land surface processes, namely, the surface energy balance, hydrological cycle, carbon cycle, and vegetation dynamics. However, in order to reconstruct river flows from the land use modeled water budget, the estimated water fluxes need to be routed through the landscape and river network in consideration (Arora et al., 1999).

The objective of this study was to understand the contributions and cumulative effects of two contrasting future drivers of the Tapajós hydrology: global climate change, expected to reduce river flows (Cox et al., 2004; Guimberteau et al., 2013; Joetzjer et al., 2013; Malhi et al., 2008; Sorribas et al., 2016), and deforestation, expected to increase surface runoff (Abe et al., 2018; Andréassian, 2004; Bosch & Hewlett, 1982; Brown et al., 2005; Bruijnzeel, 1990; Guimberteau et al., 2017; Lee et al., 2018; Sahin & Hall, 1996; Stickler et al., 2013). The specific question we investigate is how future scenarios of climate and land use affect the water budget components (precipitation, evapotranspiration, and runoff) and consequently the magnitude and variability of river flows.

Answering this question is directly relevant to the ongoing debate surrounding the concept of stationarity in the context of water infrastructure design (Galloway, 2011; *Milly* et al., 2015 and 2008). In addition to the scientific insights gained from this study, the answers to this question are extremely relevant to the improvement of water resources management and development planned in the Tapajós and the broader Amazon region.

2. Materials and Methods

2.1. Description of the Study Area

The Tapajós River basin drains an area of 476,674 × 10^6 km^2 in central north Brazil (Figure 1). The river system is the fifth largest tributary of the Amazon and flows northward on the territories of the States of Mato Grosso, Pará, and Amazonas. The main tributaries flowing into the Tapajós are the Jamanxim, Teles Pires, and Juruena Rivers.

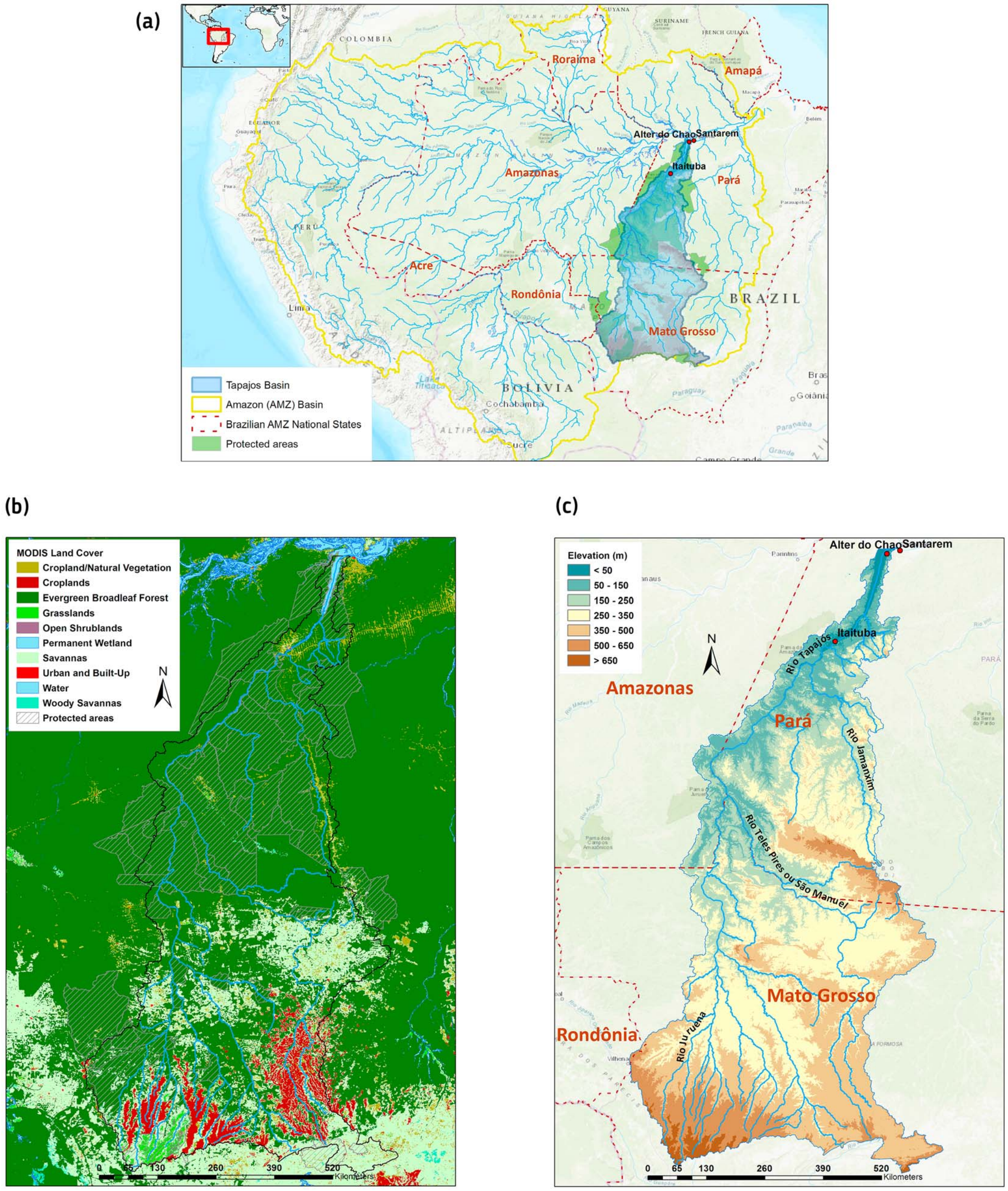

Figure 1. Tapajós River basin: (a) localization within the Amazon Basin, (b) land cover and protected areas as of 2012 (Channan et al., 2014), and (c) elevation, main tributaries, main urban areas, and state borders.

The basin's elevation ranges from about 800 m above sea level in its southern part to few meters above sea level at the confluence with the Amazon River (ANA, 2011). The soil varies from deep soils within the Brazilian shield in the south to soft alluvial deposits typical of the plains in the northern part, closer to the Amazon River. The region has a tropical climate with a long rainy season between September and May and a dry season between June and August. Precipitation ranges from about 1,500 in the south to 2,900 mm/year in the northern part of the basin (ANA, 2011; Mohor et al., 2015). Land cover varies from typical Cerrado savannas in the south to tropical evergreen rainforest in the north. The portion of the basin laying in Mato Grosso State has been heavily deforested in the past to open space for agriculture (Figure 1b), with different consequences for the local hydrological and atmospheric circulation as shown in other studies focused on the Amazon (Aragão et al., 2014; Hayhoe et al., 2011; van der Ent et al., 2010; Vergara & Scholz, 2011). The northern part of the basin in the States of Pará and Amazonas is largely protected for social (indigenous lands) or environmental reasons (state and national parks), except for the areas closer to the cities of Santarem and Itaituba (Figure 1c) where agriculture and pasture have replaced large areas of forest (ANA, 2011; Aragão et al., 2014). The Tapajós River basin economy is mainly based on agribusiness and related services.

2.2. Model Description

Vertical water fluxes through the biosphere of the Tapajós River basin were simulated using ED2. This land surface model simulates the coupled carbon, energy, and water fluxes as well as the resulting longer-term dynamics of ecosystem composition and structure within climatological grid cells (Hurtt et al., 2013; Medvigy et al., 2009; Moorcroft et al., 2001).

Operating at multiple temporal and spatial scales, ED2 simulates ecohydrological processes, including plant growth and mortality, phenology, soil biogeochemistry, and vertical water fluxes (Longo, 2014; Longo, Knox, Levine, et al., 2019; Longo, Knox, Medvigy, et al., 2019; Medvigy et al., 2009). The subgrid heterogeneity within each climatological grid cell is represented by a series of dynamic tiles of heterogeneous vegetation, a feature which makes ED2 ideal for simulating landscape mosaics where a mixture of natural and disturbed land cover types is found (Albani et al., 2006; Longo, Knox, Levine, et al., 2019; Medvigy et al., 2009; Medvigy & Moorcroft, 2012; Swann et al., 2015). Both natural disturbances—including plant mortality due to changing environmental conditions—and human-driven disturbances—fires, deforestation, and forest logging—are considered in the biosphere dynamics simulated with ED2 (Albani et al., 2006; Medvigy et al., 2009). Such disturbances are incorporated in a separate subroutine that tracks annual transitions among primary vegetation, secondary vegetation, and agriculture (cropland and pasture; Albani et al., 2006). For purposes of representing the typical structure and composition of tropical ecosystems, four different plant functional types are represented in ED2: early successional trees (fast growing, low wood density, and water needy), midsuccessional trees, late-successional trees (slow growing, shade tolerant, and high wood density), and C_4 grasses (including also pasture and agriculture; Longo, Knox, Levine, et al., 2019; Longo, Knox, Medvigy, et al., 2019; Swann et al., 2015; Longo, 2014; Medvigy et al., 2009).

ED2 computes water, carbon, and energy fluxes through the biosphere (vegetation, air-canopy space, and soils), leading to daily estimates of subsurface and surface runoff at the grid cell level. Groundwater exchange through soil layers is computed as a function of soils' hydraulic conductivity, soil temperature, and terrain topography. For more detailed descriptions of most processes computed, we refer the reader to the literature available on the ED2 model (Longo, 2014; Longo, Knox, Levine, et al., 2019; Longo, Knox, Medvigy, et al., 2019; Medvigy et al., 2009; Moorcroft et al., 2001; Zhang et al., 2015).

In the native ED2 formulation, estimates of daily runoff are computed for each climatological grid cell independently (Figure 2), that is, disregarding flow accumulation and attenuation as water propagates laterally through the landscape. A hydrological routing scheme adapted from MGB-IPH, a rainfall-runoff model extensively tested for large river basins in the Amazon and other regions of South America (Collischonn et al., 2007), was therefore linked to the model in order to estimate daily flows that are comparable to gauge measurements taken in the rivers. Although the MGB-IPH was later improved using methods more appropriate for fine-scale dynamics (Pontes et al., 2015; Paiva, Collischonn, & Buarque, 2013), given the regional nature of our application, we used the conventional Muskingum-Cunge approach. This is a mathematical approach using a finite-difference method as a function of river length, width, depth, roughness, and terrain elevation and slope to calculate the flow propagation through the landscape. The resulting ED2+R model (Pereira et al., 2017) estimates the daily water volumes through all cells in a river drainage network. The native MGB-IPH model includes four submodels: soil water balance, evapotranspiration, intracell flow propagation, and intercell routing through the river network. Only the catchment and river routing methods were integrated in the ED2+R (further details in Pereira et al., 2017). ED2+R distributes surface and subsurface daily runoff among three physical reservoirs that represent differences in hydraulic residence time through the soil. When water moves from the landscape into rivers, ED2+R calculates flow routing using the Muskingum-Cunge equation. The routing component of the model was calibrated by dividing the Tapajós basin into seven subbasins, each of them with a corresponding gauge for which historical daily river flow observations were available (Figure 2). A detailed description of the ED2+R integration and the calibration procedure can be found in Pereira et al. (2017). This reference describes also the

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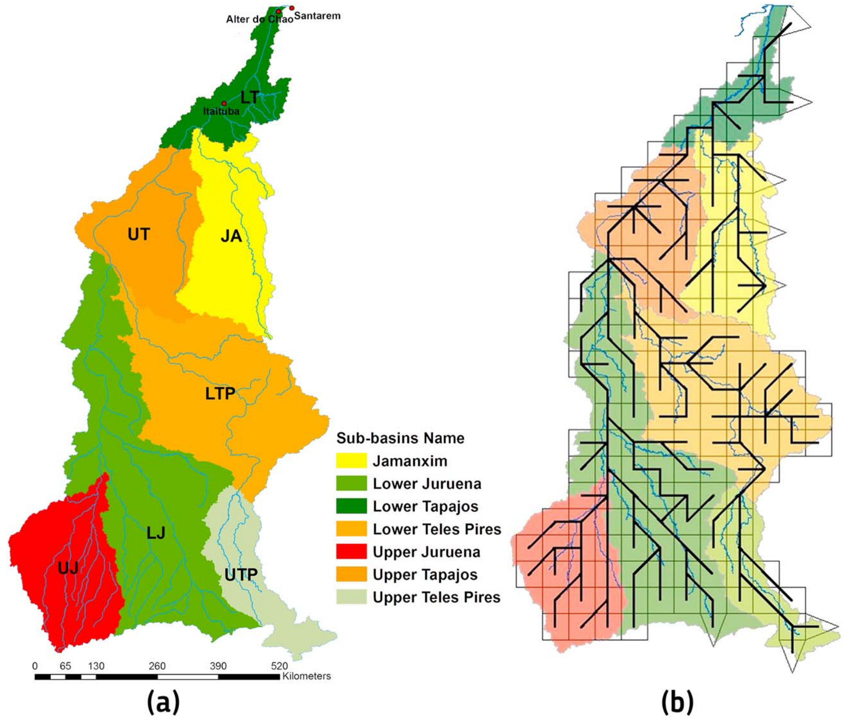

Figure 2. (a) Division of the Tapajós basin into seven subbasins (Upper Juruena = UT; Lower Juruena = LJ; Upper Teles Pires = UTP; Lower Teles Pires = LTP; Jamanxim = JA, Upper Tapajós = UT; and Lower Tapajós = LT). (b) The domain is subdivided in cells with 0.5° resolution (approximately 55 km; redrawn from Pereira et al., 2017).

configuration of the model for the Tapajós River basin: the main parameters used and the model performance statistics are summarized in Tables S1 and S2 in the supporting information, while the input variables needed and their source data are summarized in Table 1. The model's performance in terms of the ability to reproduce the water volumes is generally high throughout the basin, while its ability to reproduce the flow seasonality is higher in the downstream portion of the basin and lower in the headwaters. These limitations are likely linked to the complexity of the deep sandy soils in the headwater of the Tapajós basin that could not be fully represented by a land surface model integrated with a routing scheme as the ED2+R model (Pereira et al., 2017). A detailed description of the main hydrological methods used for the simulations was presented in Arias et al. (2018), and we refer the reader to this paper for further information about the mathematical representation of the physical processes in the ED2+R model. The ED2+R model was successfully used to study the separate and combined effect of deforestation and climate dynamics on historical river flows in Arias et al. (2018).

2.3. Scenarios Description

The ED2+R model was forced using past and future climate data derived from the coupled Earth System Model (ESM) HadGem2-ES of the UK Met Office Hadley Centre (Bellouin et al., 2007; Collins et al., 2008; Collins et al., 2011; Johns et al., 2006; Jones et al., 2011; Martin et al., 2006; Ringer et al., 2006), and additional sensitivity tests were performed using future climate data from the IPSL-CM5 of the French Institute Pierre Simon Laplace (Dufresne et al., 2013; Hourdin, Foujols, et al., 2013; Hourdin, Grandpeix, et al., 2013; Mignot et al., 2013; Szopa et al., 2013) and the GISS-E2 of the NASA Goddard Institute for Space Studies (Miller et al., 2014; Nazarenko et al., 2015; Schmidt et al., 2014; Shindell et al., 2013) from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012). The choice of the HadGem2-ES was motivated by its effectiveness in reproducing the climate in the Amazon as tested in previous studies (Good et al., 2013; Joetzjer et al., 2013; Sillmann et al., 2013), both with respect to other CMIP5 and previous generation CMIP3 ESMs. The IPSL-CM5 and the GISS-E2 were selected because they represent the end points of predicted rainfall in the Amazon, with IPSL-CM5 being the wettest and GISS-E2 being the driest projection (Joetzjer et al., 2013). Future climate projections from different models are, in fact, highly variable in the Amazon (e.g.,

Table 1
Main Variables Used in the Simulations and Data Source

Data group	Variable(s)	Resolution	Source
Meteorological forcing	Atmospheric temperature, specific humidity, downward shortwave and longwave radiation, wind speed, air pressure, and precipitation	3-hourly (temporal) 1° (spatial)	Observed—Sheffield et al. (2006) Projections: HadGem2-ES—Jones et al. (2011); Collins et al. (2011); Collins et al. (2008); Bellouin et al. (2007); Johns et al. (2006); Martin et al. (2006); Ringer et al. (2006) IPSL-CM5—Dufresne et al. (2013); Hourdin et al. (2013); Hourdin et al. (2013); Mignot et al. (2013); Szopa et al. (2013) GISS-E2—Miller et al. (2014); Nazarenko et al. (2015); Schmidt et al. (2014); Shindell et al. (2013)
Carbon dioxide concentration	CO_2 concentration	—	378 ppm
Topography (DEM)	Digital Elevation Model	90 mt (spatial)	SRTM, Shuttle Radar Topography Mission 90-mt resolution
Soil	Soil types and texture	1° (spatial)	Quesada et al. (2010) and Cosby et al. (1984), IGBP-DIS global soil data (*Global Soil Data Task* 2014)
Land use	Fraction of land use—transitions among agriculture and primary and secondary vegetation	1° (spatial)	Hurtt et al. (2006) and Soares-Filho et al. (2006)

Sorribas et al., 2016; Guimberteau et al. 2017). The selection of the two extreme ESMs allowed to analyze the range of variability accounting for the uncertainty linked to the choice of climate models. The baseline scenario was obtained using HadGem2-ES historical simulations for the period 1986–2005; future simulations (2026–2045) were computed using two distinct climate change Representative Concentration Pathways (RCP 4.5—moderate and RCP 8.5—extreme climate change; Vuuren et al., 2011).

Leaving aside the most extreme ESMs, in order to give to the reader an overview of the possible change in the climatological variables, we describe more in detail the characteristics of the features of the HadGem2-ES, keeping in mind that these values might be affected by a certain degree of uncertainty that will be quantified by comparing the outcomes resulting by the use of the three models. Mean annual precipitation as computed by HadGem2-ES historically ranged between 1,559 and 2,416 mm/year over the study domain. When the historical precipitation spatial distribution is compared to future conditions, however, both RCPs considered project a general decrease in precipitation over the case study area (Figure 3). This negative tendency in precipitation projections is clear in both climate change scenarios, with reductions ranging between 35 and 133 mm/year for the moderate scenario (RCP 4.5—Figure 2b) and between 29 and 180 mm/year for the extreme one (RCP 8.5—Figure 2c). Statistically significant drier conditions, for both future scenarios, are expected in particular in the central and southern parts of the basin. The statistical significance of the described changes was assessed by applying a two-sample *t* test at 5% significance level. Shaded values in the Figures 3, 4, 7, and 8 are not statistically significant.

The spatial distribution of average temperature within the river basin, as computed by the HadGem2-ES ESM, ranges from 22 °C in the southern part to 26 °C in the north (Figure 4a). Future projections show an increase in average monthly temperatures of about 1.3 to 1.7 °C for the moderate climate change scenario (RCP 4.5—Figure 4b) and about 1.6 to 1.9 °C for the severe climate change scenario (RCP 8.5—Figure 4c). Warming conditions are predicted to be more evident in the central and southern parts of the basin. These values, taking into account the different time periods, are in line with the projections of the ensemble of 25 models from the CMIP5 that projected changes for the Amazon region by 2100, considering the pessimistic RCP8.5 scenario, quantified in an 11% decrease of annual precipitation and an increased temperature ranging between 3 and 5° (Christensen et al., 2013).

Land use data were prescribed from two widely used data sets. Historical patterns of land use were extracted from *Hurtt* et al. (2011 and 2006), a global land transition data set being used frequently in ESMs. Future land use patterns were prescribed based on two different simulations of deforestation from Soares-Filho et al.

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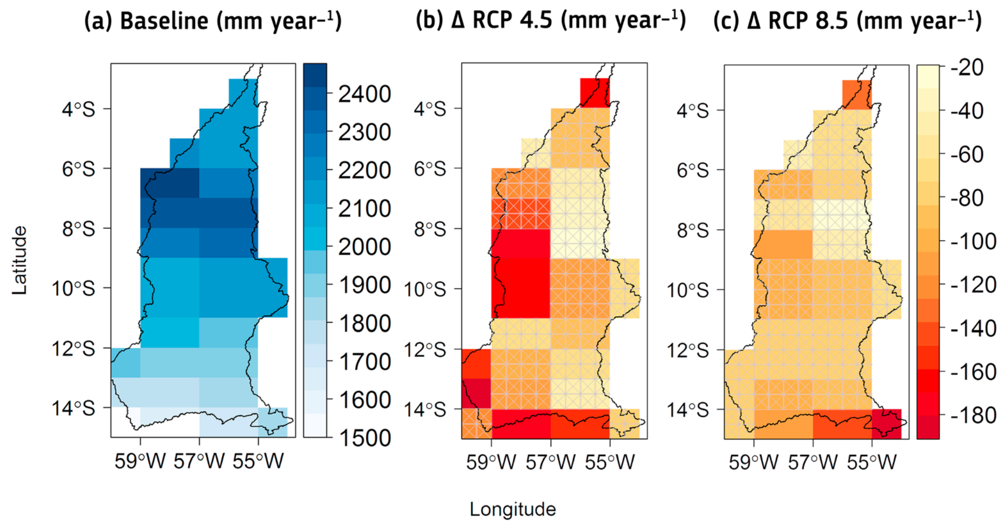

Figure 3. (a) Average annual precipitation (mm/year) for the baseline scenario 1986–2005. (b) Change (Δ) in precipitation with respect to the baseline scenario for the moderate climate change scenario—RCP 4.5 for 2026–2045. (c) Change (Δ) in precipitation with respect to the baseline scenario for the severe climate change scenario—RCP 8.5 for 2026–2045. Pixels marked with ⊠ are not statistically significant at 95% confidence level (*p* values > 0.05 using a two-sample *t* test). RCP = Representative Concentration Pathway.

(2006): Governance and Extreme Deforestation scenarios (Figure 5). The Soares-Filho et al. (2006) study was based on the high deforestation rates recorded in the period between 1990 and 2004 before the public interventions on the soybean and beef supply chains (Nepstad et al., 2014), and the introduction of the 2012 forest code by the Brazilian Government, whose economic incentives for the protection of the forested areas in privately owned land were found inadequate in Azevedo et al. (2017). The Extreme Deforestation scenario (Figure 5c) was determined by projecting to 2050 the high rate of deforestation recorded in the period before 2004. In the past few years, the likelihood of reaching this extent of deforestation seemed considerably lower after the introduction of 2009 and 2012 forest regulations (Dalla-Nora et al., 2014) and new conservative scenarios were developed (Aguiar et al., 2016); however, this most

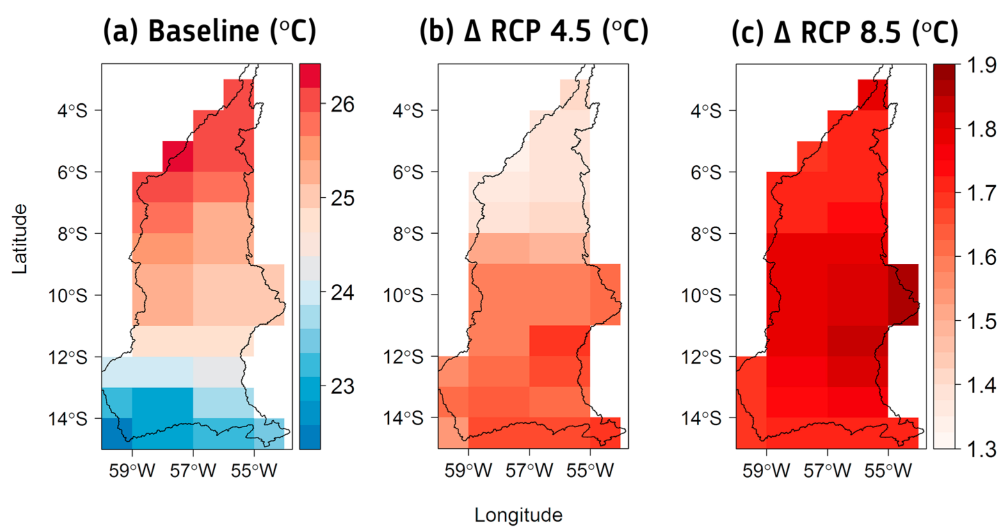

Figure 4. (a) Average temperature (°C) for the baseline scenario 1986–2005. (b) Temperature change with respect to the baseline (Δ) for the moderate climate change scenario—RCP 4.5 for 2026–2045. (c) Temperature change with respect to the baseline (Δ) for the severe climate change scenario—RCP 8.5 for 2026–2045. All values are statistically significant at 95% confidence level (two-sample *t* test). RCP = Representative Concentration Pathway.

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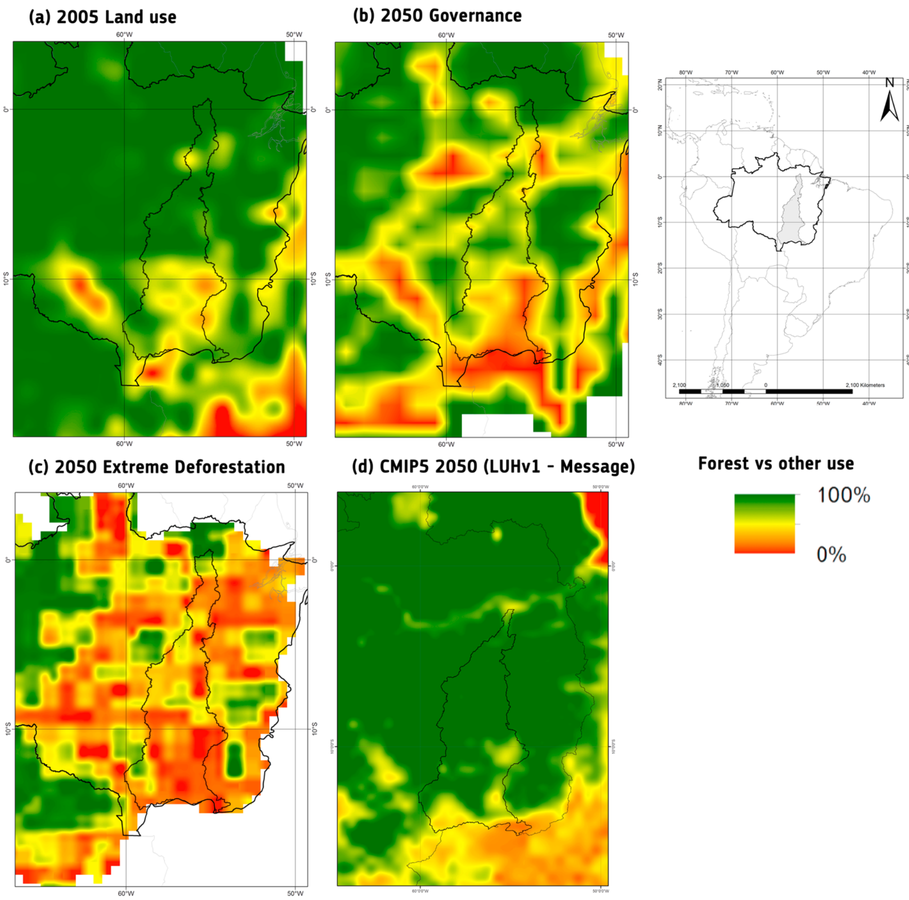

Figure 5. Tapajós River basin land cover 2005 (a) versus two different 2050 scenarios: Governance (b) and Extreme Deforestation (c). Land use scenarios for the CMIP5 climate projections (d). Green indicates 100% forest cover, red 0%. Maps created using data from Hurtt et al. (2006), Hurtt et al. (2011), and Soares-Filho et al. (2006).

extreme scenario was included in this study in order to evaluate the effects of extreme conditions (as in Von Randow et al., 2019). The more optimistic—and realistic—scenario, Governance (Figure 5b), was created to represent the effects of regulations proposed for conservation of the Amazon forests (Soares-Filho et al., 2006). It has to be pointed out, however, that recent political changes in the Brazilian administration reopened the debate about the protection of the Amazon forest in light of the agricultural expansion in the region (Artaxo, 2019; Nature Editorials, 2018; Tollefson, 2018). This raised the level of uncertainty with respect to the future of forest conservation areas in the northern Tapajós River basin, already threatened by the increased accessibility due to road development. As pointed out in Rochedo et al. (2018), in fact, a weakened environmental Governance could increase significantly the level of deforestation also in the protected areas. For this reason, the extreme scenario from Soares-Filho et al. (2006) was also used in this analysis. In the setup for the CMIP5 simulations (as described in Jones et al., 2011), the HadGem2-ES ESM model was forced using the Land Use Harmonization v.1 (LUH1) data (Hurtt et al., 2011). The LUH1 2050 scenario predicts significantly less deforestation in this portion of the Brazilian Amazon, especially in the central and northern parts of the Tapajós basin (Figure 5d), when compared to both the Governance and Extreme Deforestation scenarios. This might have created some degrees of inconsistency in the projections combining climate and land use change that is difficult to quantify.

Different combinations of the future scenarios of land use and climate change described above were simulated using the ED2+R model. Rather than considering an exhaustive number of scenarios, the experimental setup was designed to appropriately assess the marginal contributions and cumulative effects of climate change and land use conversion. A total of six climate and land use scenarios were considered (Table 2).

Table 2
Climate and Land Use Change Scenarios Produced for the Flow Analysis

Land use Climate	2005 land use	2050 Governance	2050 extreme deforestation
1986–2005 HadGem Historical	Baseline		
2026–2045 Moderate (rcp 4.5)	noLU_rcp45	GOV_rcp45	
2026–2045 Extreme (rcp 8.5)	noLU_rcp85	GOV_rcp85	EXT_rcp85

All of them were simulated for a total of 20 years at daily time steps. The choice of the simulation length was made in order to efficiently balance the trade-off between the quality of the simulation results and the constrained time and capacity of computing resources. For the same reason, we opted for a 20 years window, respect to a more usual 30 years one, after testing that the range of variability in the climate variables used spanned by the two temporal windows could be quantified in a similar order of magnitude. The selection of the years for the future projections (2026–2045) was determined by the availability of the 3-hourly projections at the moment of the simulation setup.

2.4. Bias Correction of Simulated Streamflows

The streamflows resulting from the analysis were bias corrected in order to minimize the inaccuracies arising from systematic biases in the ESM simulations of the Amazon's contemporary climate (Randall et al., 2007; van Vliet et al., 2013). Several bias correction methods applied to hydrological simulations of future climate scenarios have been used in previous studies (e.g., Eisner et al., 2012; Hempel et al., 2013; Muerth et al., 2013; Rojas et al., 2012). One approach has been to downscale and bias correct the meteorological inputs, typically precipitation and temperature (e.g., Guimberteau et al., 2017; van Vliet et al., 2013). As discussed in Hashino et al. (2007), several techniques are being applied to bias correct meteorological forcing data: simple approaches calculate a "delta factor" (e.g., Diaz-Nieto & Wilby, 2005), but other more sophisticated statistical approaches also exist (e.g., Fang et al., 2015; Moghim et al., 2016). In other cases, original General Circulation Model data have been used to force a regional climate model specifically calibrated for the domain under consideration (e.g., Jacob et al., 2007). Both these methodologies are not free of criticism (Li et al., 2017; Chen et al., 2013; Ehret et al., 2012). In other applications—especially in case of short-term forecasts—the bias correction has been applied directly to the streamflow resulting from the hydrological analysis (e.g., Bogner & Pappenberger, 2011; Verkade et al., 2013; Yuan & Wood, 2012; Zalachori et al., 2012). In this study, we chose this latter approach: applying a simple bias correction to the cumulative distributions resulting from our simulations of river flows from ED2+R. The reasons for using this approach were twofold: first, the bias-corrected data for the HadGem2-ES were produced within the ISI-MIP project (Hempel et al., 2013; Warszawski et al., 2014) but at daily time steps only, while the ED2 land surface model requires more detailed time scale inputs (we used the three hourly original data made available by the U.K. Meteorological Office, later downscaled at hourly time steps). Second, statistical bias correction of meteorological data is typically applied only to temperature and precipitation, thereby creating physical inconsistencies with the other variables needed for the land surface model forcing (longwave and shortwave radiation, humidity, pressure, and wind, as described in Table 1). Methodologies for the calculation of bias corrected surface downward longwave and shortwave radiation data were made available only recently (as reviewed in Lange, 2018).

In order to carry out the bias correction, flow duration curves—representing the probability of exceedance for the range of flows—of the baseline scenario (Table 2) at the seven different subbasins were compared with the distribution of the corresponding historical observations—using data from the Brazilian Water Agency (Agência Nacional de Águas—ANA) and the Observation Service for Geodynamical, hydrological, and biogeochemical control of erosion/alteration and material transport in the Amazon, Orinoco, and Congo Basins (HYBAM). The ratio between the two distributions was used as a multiplier to correct all the simulated flows for the specific subbasin (Figure 6). The approach was replicated for each of the seven subbasins. As shown in Figure 6a, the simulation results, prior to the bias correction (blue dotted line), overestimate the low values of flow and underestimate the middle and high values (black line). The bias correction procedure aligns the flow duration curves of the simulated values (red dotted line) to the observed

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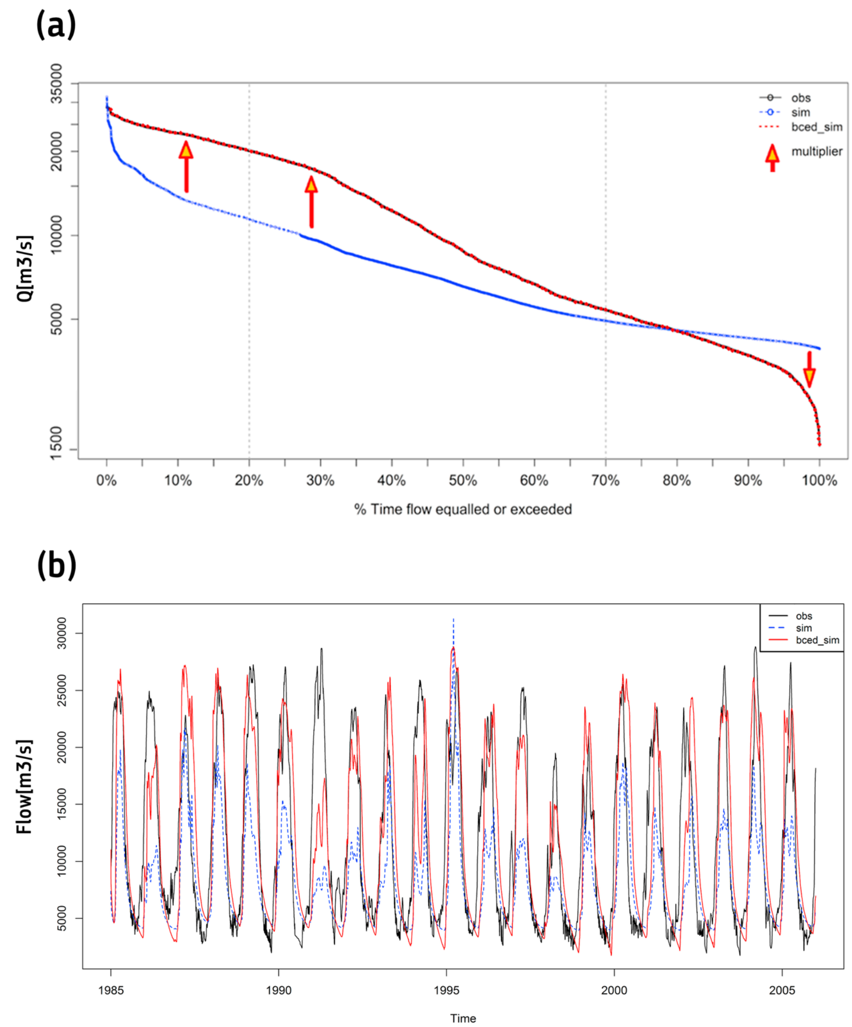

Figure 6. Bias correction of the streamflow at Itaituba-Lower Tapajós subbasin (Figure 2a). (a) Flow Duration Curve of the baseline (1986–2005) scenario (sim—dotted blue line), observed (obs—bold black line), and bias corrected (bced_sim—dotted red line). Flow (m^3/s) on the *y* axis and percentage of the time of exceedance of the specific threshold on the *x* axis. (b) Comparison of the three time series: simulated flow (sim—dotted blue line), observed (obs—bold black line), and bias corrected (bced_sim—bold red line).

ones (black line), reducing considerably the variation of the simulated hydrograph from the observed one (Figure 6b).

3. Results

3.1. Future Variations of Evapotranspiration and Runoff

Climate change is projected to increase evapotranspiration rates in the primarily forested areas in the northern part of the Tapajós River basin (Figure 7). The values, historically (1986–2005) averaging between 1,300 and 1,750 mm/year in the basin (Figure 7a), are expected to increase up to 73 mm/year in both scenarios (Figures 7b and 7c). A different response is seen in the agricultural areas in the southern part of the basin (Figures 7b and 7c), where the estimated decrease ranges between 18 mm/year (RCP 4.5, Figure 7b) and 32 mm/year (RCP 8.5, Figure 7c). The contrasting effect is explained by the differing response of the various plant functional types to increasing temperature and solar radiation. Grassland, shrubland, and agricultural areas are vulnerable to the combination of decreasing precipitation and increasing temperature and solar radiation, with the result of having generally drier conditions. In contrast, forested areas are relatively

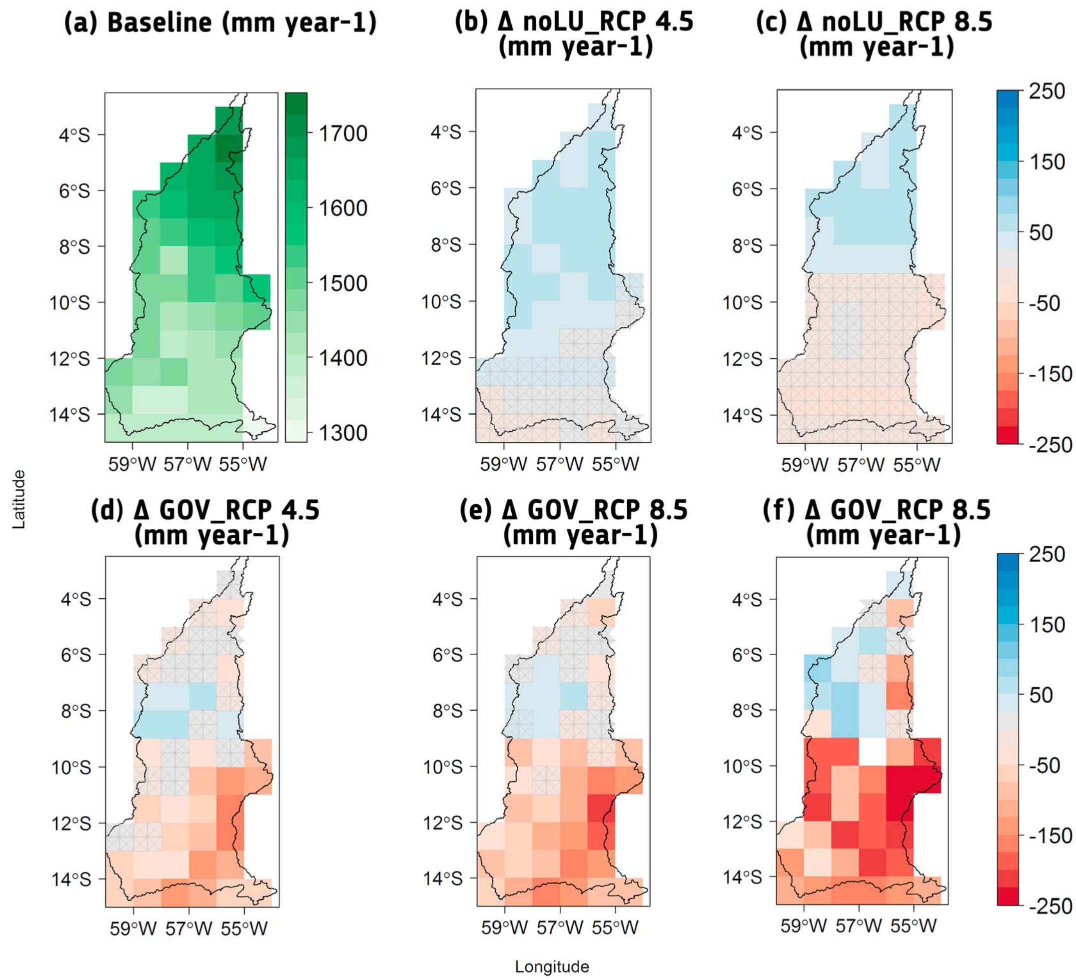

Figure 7. Average yearly evapotranspiration (mm/year) from the ED2 simulations using the scenarios summarized in Table 1. (a) Historical/baseline scenario; change with respect to the baseline (Δ) for the scenarios. (b) No land use and moderate climate change (noLU_rcp45). (c) No land use and severe climate change (noLU_rcp85). (d) Moderate land use (Governance) and climate change (GOV_rcp45). (e) Moderate land use (Governance) and severe climate change (GOV_rcp85). (f) Severe land use (Extreme) and severe climate change (EXT_rcp85). Pixels marked with ⊠ are not statistically significant at 95% confidence level (p values > 0.05 using a two-sample t test). RCP = Representative Concentration Pathway.

resilient to variations in precipitation, temperature, and solar radiation, primarily due to the ability of forest trees to draw water resources from the deeper soil layers.

The introduction of land use change (mainly deforestation and conversion to cropland and pasture in this area) in the simulations reduces evapotranspiration throughout the basin. This trend is proportional to the degree of change in land use: the Extreme Deforestation scenario (with decrease up to 296 mm/year) has a larger impact on evapotranspiration (ET) with respect to the moderate scenario (decrease up to 214 mm/year; Figures 7d–7f).

Changes in precipitation, combined with increasing temperature, and solar radiation that characterize the future climate scenarios, are predicted to cause an overall decrease in the surface and subsurface runoff in the Tapajós River basin by up to 180 mm/year for RCP 4.5 (Figure 8b) and 157 mm/year for RCP 8.5 (Figure 8c), substantially decreasing the historical values ranging between 140 and 800 mm/year (Figure 8a). The ED2+R model simulations confirm the expected impacts of deforestation on runoff: results obtained under the different land use change scenarios show increased surface and subsurface runoff. The spatial distribution and the intensity of runoff changes were correlated with the deforestation rate in the different parts of the basin, under both land use change scenarios (Figures 8d–8f). The greatest increase in runoff (up to 174 mm/year for the moderate deforestation—Figure 8e and 236 mm/year for the Extreme

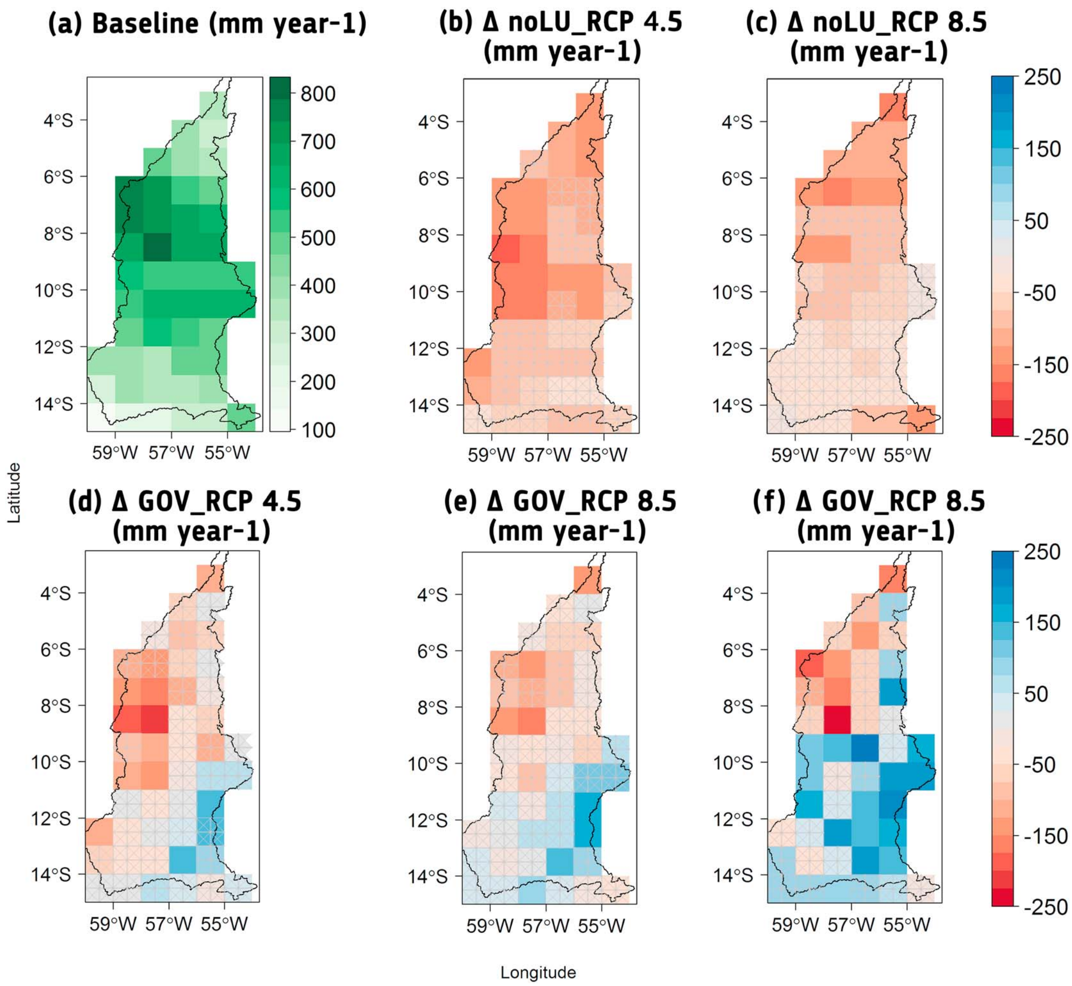

Figure 8. Average yearly runoff (mm/year) from the ED2 simulations using the scenarios summarized in Table 1. (a) Historical/baseline scenario; change with respect to the baseline (Δ) for the scenarios. (b) No land use and moderate climate change (noLU_rcp45). (c) No land use and severe climate change (noLU_rcp85). (d) Moderate land use (Governance) and climate change (GOV_rcp45). (e) Moderate land use (Governance) and severe climate change (GOV_rcp85). (f) Severe land use (Extreme) and severe climate change (EXT_rcp85). Pixels marked with ⊠ are not statistically significant at 95% confidence level (p values > 0.05 using a two-sample t test). RCP = Representative Concentration Pathway.

Deforestation scenario—Figure 8f) can be observed in those areas in the lower and middle parts of the basin characterized by a historical higher forest cover, namely, Upper Tapajós, Lower Juruena, and Lower Teles Pires.

3.2. Impacts of Climate Change and Land Use on River Flow

We evaluated the effects of changes in climate and land use on patterns of river flow by analyzing flow projections for the future scenarios at Itaituba, in the lower Tapajós subbasin (see location in Figure 2). Figures 9–11 show the flow duration curves, the monthly boxplot of the daily flow values, and the daily flow values (average, minimum, and maximum), respectively, of the scenarios described in Table 2. Climate change is predicted to consistently reduce daily flows throughout the year as suggested by the flow duration curves at Itaituba (Figure 9a). This could be translated into a reduction of the volume of water available in the river system and a reduction of the highest and lowest peaks.

Future climate conditions are expected to cause a temporal shift in flow seasonality, causing a delay of the beginning of the wet season by several weeks and shortening the overall duration of the wet season (Figure 10a). The seasonal peak month in streamflow is also expected to shift from the period March–April, in the baseline scenario, to the month of May. The severe climate change scenario (RCP 8.5) is not expected to exacerbate the magnitude of impacts on the river system: in some periods of the year its median values are higher than the ones associated with the moderate climate scenario (RCP 4.5; see Figures 9a and 10a). The main difference between the two scenarios is represented by the variability of the flow throughout the year; severe climate change is expected to consistently increase flow variability in both dry and wet seasons more than in the moderate scenario (Figure 10a). Both the climate scenarios are likely to reduce river flow, especially during the wet season. These trends are seen in the maximum, minimum, and average daily value of the different scenarios time series (Figure 11). Figures 11b and 11c show the shift in seasonality, the contraction of the wet season (especially with the more severe climate scenario—RCP 8.5), and the substantial reduction of the maximum and minimum daily flows.

As expected, deforestation generally leads to increased runoff. In the case of the Extreme Deforestation scenario (Figures 9c and 10c), the magnitude of effects on flow is similar in magnitude to the effect of climate change, while under the Governance scenario the effect of land use is considerably smaller than the effect of climate change (Figures 9b, 9c, 10b, and 10c). In the analysis of the flow probabilistic distributions (Figure 9), the introduction of deforestation determines a constant increase of all flow magnitudes (except the very low flows, i.e., >95% exceedance) with respect to the correspondent scenarios considering only climate change (Figures 9b and 9c). For instance, the introduction of the moderate deforestation scenario (Governance) determines approximately a 10% increase for the portion of flow distribution ranging between 10% (very high flows) and 90% (very low flows) of time equaled or exceeded with respect to the scenario considering only moderate (RCP 4.5) climate change (light blue vs. green lines in Figure 9b). Similar conclusions can be drawn analyzing the introduction of the moderate deforestation scenario (Governance) in combination with severe (RCP 8.5) climate change (dark blue vs. orange line in Figure 9c). Similar patterns, but in higher magnitude (~15%), are noticeable comparing the Extreme Deforestation scenario in addition to severe climate change (RCP 8.5; red vs. orange line in Figure 9c).

The analysis of flow duration curves (Figure 9) implies that the patterns dictated by climate variations govern future hydrological conditions, namely, the shift in seasonality and the increasing interannual variability with respect to the baseline. In addition, the analysis of the daily flow values indicates that land use change is associated with a substantial increase in flow variability in the onset of the wet season, specifically in the period between February and March (Figures 10b, 10c, and 11d–11f). The scenario characterized by the combination of severe climate change and extreme land use change (EXT_rcp85) is expected to increase the variability of both higher and lower flows (Figures 10c, 10d, and 11f). The results associated with the moderate deforestation scenario (Governance) are similar in direction but smaller in magnitude (Figures 10c, 10d, 11d, and 11f).

3.3. Analysis of the Uncertainty Brought by Different Climate Models

The most recent generation of climate models (CMIP5) has made a considerable progress in the representation of the present day precipitation patterns in the Amazon region with respect to the previous generation (Joetzjer et al., 2013). There is, however, a large range of uncertainty in flow projections associated with climate models (Shrestha et al., 2016; Sorribas et al., 2016). Global climate model uncertainty was considered in this study by comparing the outputs of the HadGem to two other ESMs: the IPSL-CM5 and the GISS-E2. In order to account for a wider range of variability, we ran additional simulations using the most extreme climate scenarios (RCP 8.5) in combination with the most moderate degree of deforestation (2050 Governance scenario) and evaluated the differences between the three ED2+R simulation outputs. Note that the cases presented in this section are the results without applying any bias correction as this is a sensitivity test to evaluate the range uncertainty attributable to the choice of climate models. Considering the three climate model projections, while keeping the land use constant, it is evident that the three models span a wide range of results (Figure 12). Given the difference among flows projected by the three models, our results indicate that the uncertainty is lower for low flows, while the degree of variability is higher for flows with a percent exceedance below 50% (Figure 13b).

3.4. Spatial Variability of River Flow Projections

Future climate and land use scenarios are expected to impact river flows in a nonhomogeneous manner throughout the basin (Figure 13). The graphs shown in this section show the percentage variation from the baseline flow duration curve of the five future scenarios combining climate and land use change. The

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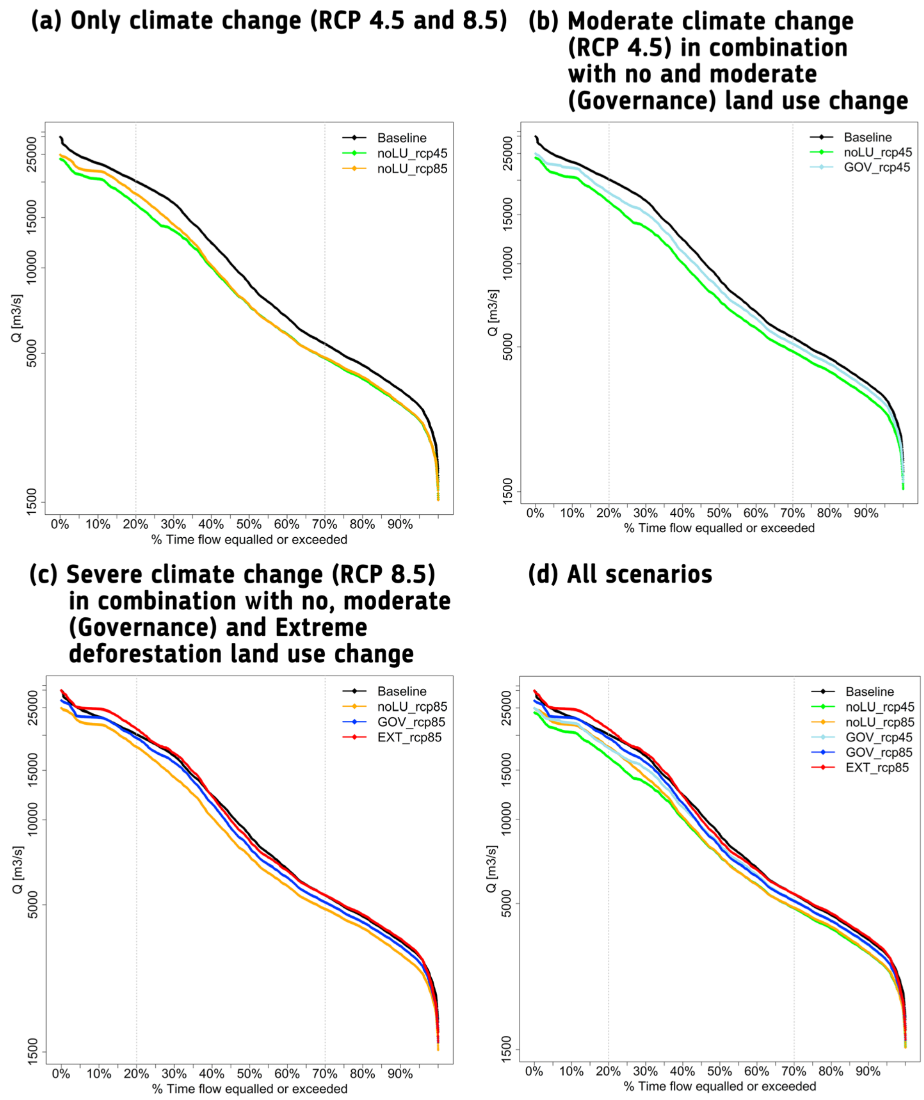

Figure 9. (a–d) Flow duration curve of the baseline (1986–2005) and future (2026–2045) climate and land use scenarios at Itaituba. Flow (m^3/s) is shown on the *y* axis and percentage of the time of exceedance of the specific threshold on the *x* axis. Baseline scenario in black, no land use and moderate climate change (noLU_rcp45) in green, no land use and severe climate change (noLU_rcp85) in orange, moderate land use (Governance) and climate change (GOV_rcp45) in light blue, moderate land use (Governance) and severe climate change (GOV_rcp85) in dark blue, and severe land use (Extreme) and severe climate change (EXT_rcp85) in red. RCP = Representative Concentration Pathway.

Upper Juruena subbasin is the portion of the case study area where the lowest impacts occur (Figure 13g), while the largest modifications to the streamflow occur in the Jamanxim river (Figure 13c). Except for the Jamanxim subbasin, the highest variations are registered in the part of the distributions reserved to the highest flow values, thus associated with the wetter portion of the years (exceedance time <40%). The general contrasting trends of climate (green and orange lines) and land use change (light blue, dark blue, and red lines) are evident for all subbasins. Moreover, the increased flows throughout the distribution associated with the introduction of deforestation in the simulations are particularly evident in the subbasins where the flows are greatest: Lower Juruena (Figure 13d) and Upper and Lower Tapajós (Figures 13a and 13b, respectively). Except for the very low flows (>95% Time flow equaled or exceeded), in the Upper and Lower Tapajós, the cumulative effect of deforestation in the contributing area of the two subbasins determines an increase of the flow distribution of about 10% for the governance and 15% for the extreme scenario with respect to the corresponding scenarios considering only climate change (light blue

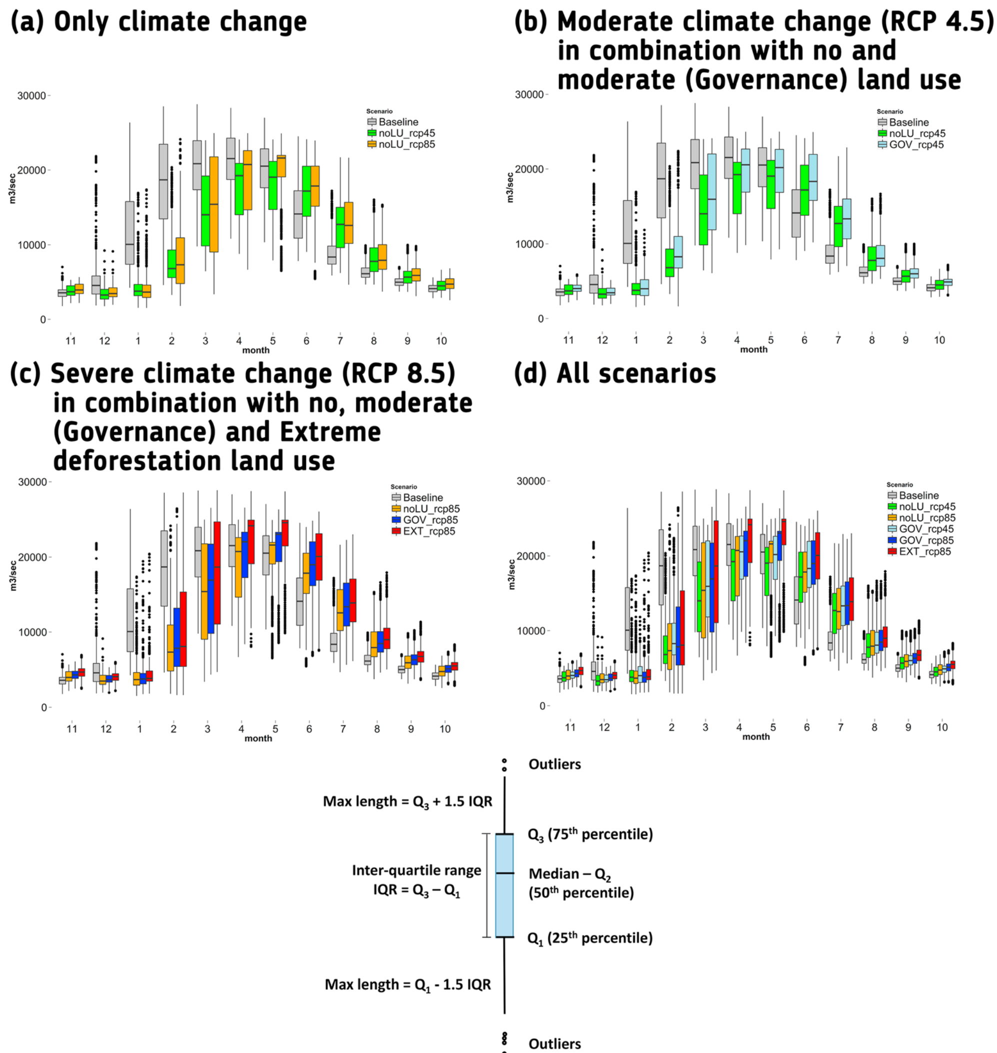

Figure 10. (a–d) Monthly box whiskers plot of the daily flow values for the baseline (1986–2005) and future (2026–2045) climate and land use change scenarios at Itaituba. On the *y* axis flow (m^3/s), on the *x* axis months (from November to October). Baseline scenario in gray, no land use and moderate climate change (noLU_rcp45) in green, no land use and severe climate change (noLU_rcp85) in orange, moderate land use (Governance) and climate change (GOV_rcp45) in light blue, moderate land use (Governance) and severe climate change (GOV_rcp85) in dark blue, and severe land use (Extreme) and severe climate change (EXT_rcp85) in red. Each of the box whiskers bar represents the distribution of the daily values for the specific month in the specific scenario for the whole simulation period. RCP = Representative Concentration Pathway.

vs. green and dark blue vs. orange for the Governance scenarios and red vs. orange lines for the Extreme Deforestation in Figures 13a and 13b, respectively). One notable aspect is the completely different behavior of the two furthest upstream subbasins: the Upper Juruena and Teles Pires (Figures 13g and 13f, respectively). In the Upper Juruena, there are little differences between the scenarios (Figure 13g), while in the Teles Pires the impacts are more substantial, especially in the upper part of the flow distribution curve (Figure 13f).

4. Discussion

The results presented in this paper are based on the analysis of the expected combined impacts of climate and land use change on the river flows in a region in the Amazon that has the largest potential for hydropower development in Brazil (MME & EPE, 2015). We explored the effects of the complex combination

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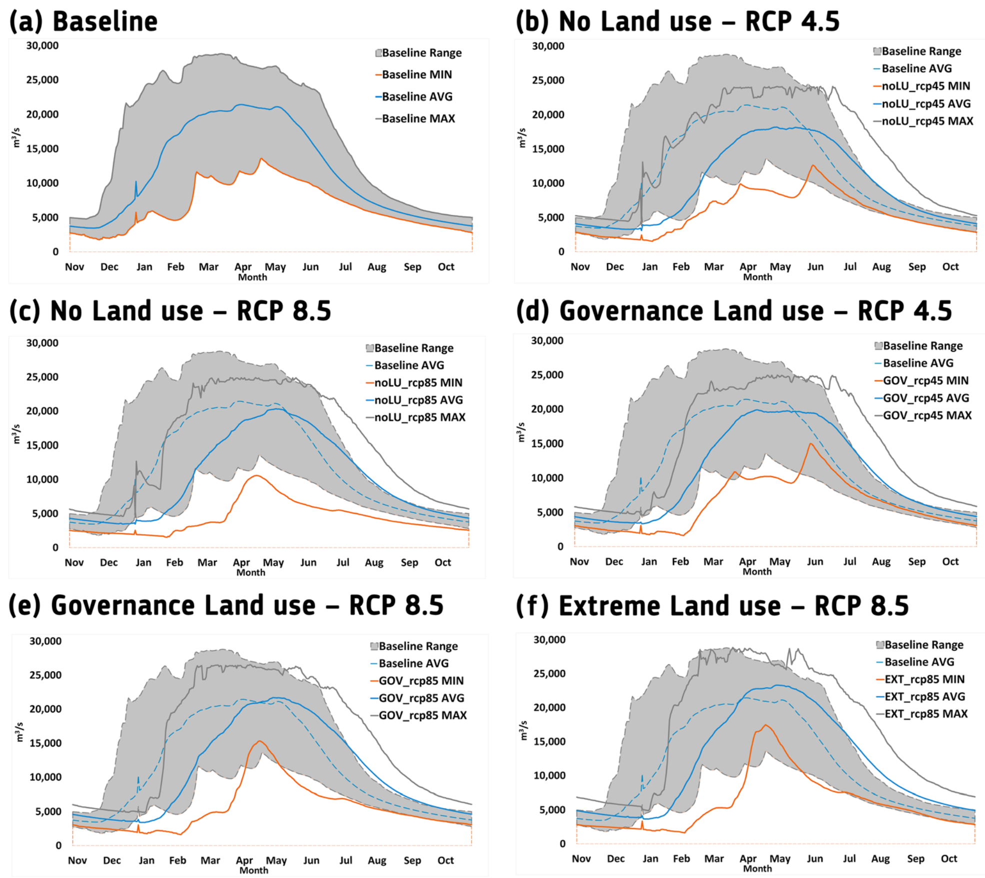

Figure 11. (a) Average, minimum, and maximum daily flow values for the baseline (1986–2005) and future (2026–2045) climate and land use change scenarios at Itaituba. On the y axis flow (m^3/s), on the x axis time (from November to October). In panels (b) to (f), the blue dashed lines represent the baseline average, minimum, and maximum and the gray shaded area the baseline variability as represented in panel (a). RCP = Representative Concentration Pathway.

of drivers through a series of simulations in a terrestrial biophysical model integrated with a routing scheme (ED2+R) forced with two scenarios calculated by an IPCC-AR5 climate model (HadGem2-ES) and two different land cover change scenarios. The uncertainty related to the climate projections was discussed by using the outputs of two additional IPCC-AR5 models (IPSL-CM5 and GISS-E2). A significant contribution of this paper to the study of future hydrological changes in large basins is the use of the land surface model (ED2)

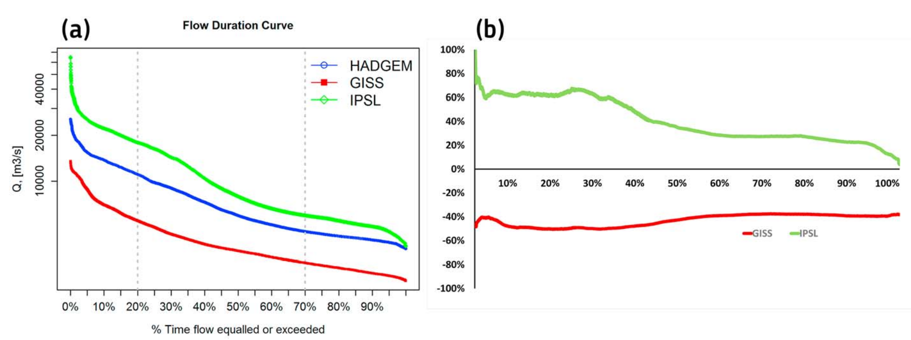

Figure 12. (a) Flow duration curve at Itaituba of the future (2026–2045) climate and land use change scenarios considering moderate land use (Governance) and severe climate change (GOV_rcp85) for the three Earth System Models: HadGem2-ES (blue), IPSL-CM5 (green), and the GISS-E2 (red). (b) Percentage variation of the IPSL-CM5 (green) and the GISS-E2 (red) respect to the Hadgem2-ES flow duration curves.

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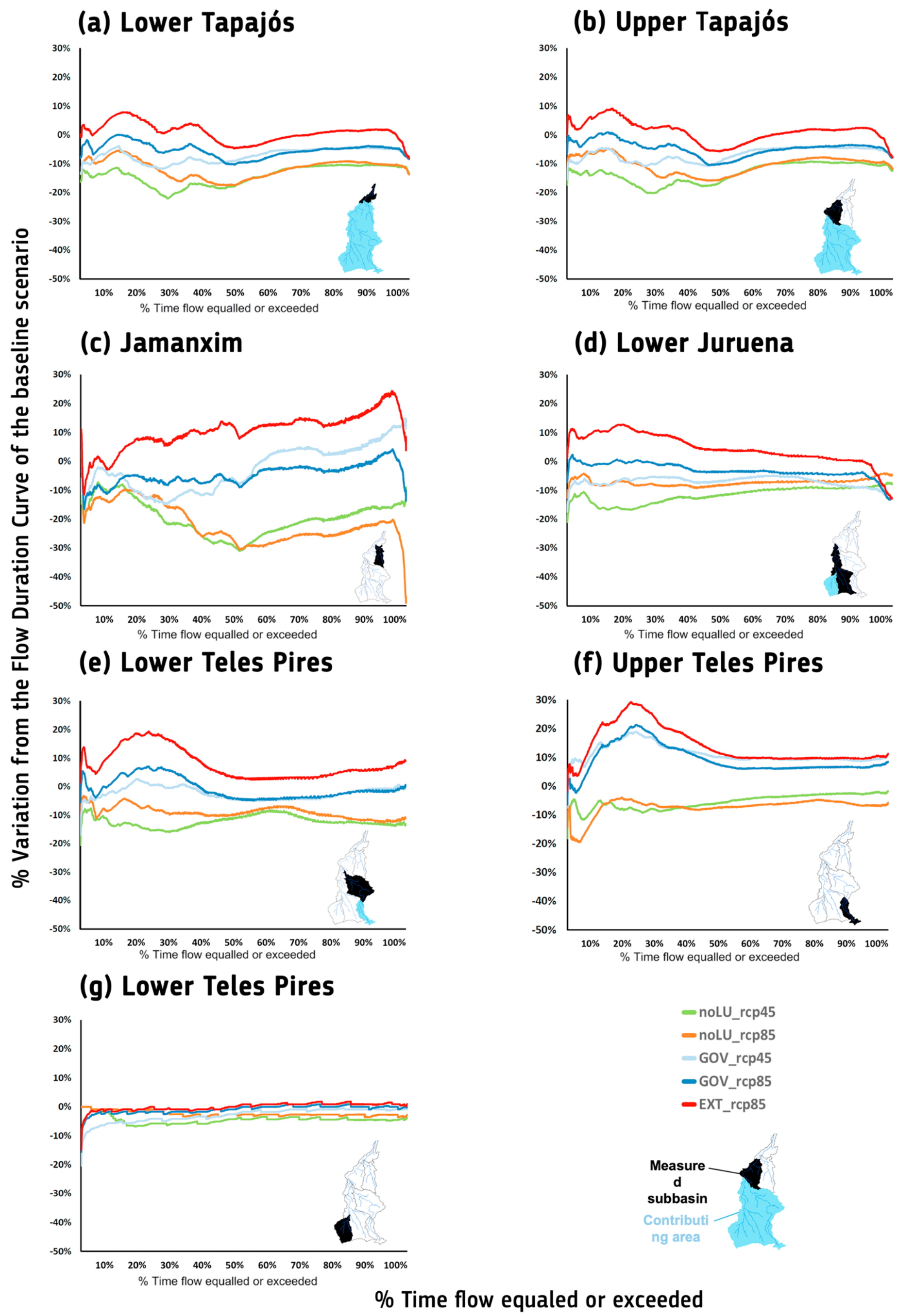

Figure 13. Percentage variation with respect to the baseline flow duration curve (1986–2005) and future (202612045) climate and land use change scenarios for the seven subbasins. On the *y* axis percentage variation (−50% to +30%), on the *x* axis percentage time of exceedance of a specific flow. No land use and moderate climate change (noLU_rcp45) in green, no land use and severe climate change (noLU_rcp85) in orange, moderate land use (Governance) and climate change (GOV_rcp45) in light blue, moderate land use (Governance) and severe climate change (GOV_rcp85) in dark blue, and severe land use (Extreme) and severe climate change (EXT_rcp85) in red.

that simulated vegetation and hydrological dynamics at the plant patch level and dynamically simulate the human and natural disturbances over time. This allowed us to analyze the separate and combined effects of climate and land use change on the hydrology of the basin. The novelty of this study lies on its contributions to the understanding of multiple drivers of environmental change on tropical river hydrology, assessed here with a detailed probabilistic evaluation of hydrological changes derived from a coupled land surface model and a hydraulic routing scheme. Moreover, the use of a bias correction methodology helps in producing realistic river flow scenarios that could be used to assess the consequences for the future socioeconomic activities linked with the water regimes in the basin as, for instance, hydropower generation.

The climate model results used for this analysis (HadGem2-ES) have been widely analyzed in literature (Good et al., 2013; Joetzjer et al., 2013; Sillmann et al., 2013) and found to reproduce adequately the climate in the Amazon (Good et al., 2013; Sillmann et al., 2013; Sorribas et al., 2016). As shown by previous studies, in fact, changes in sea surface temperature in the tropical portions of the oceans, cloud dynamics, and vegetation response are the main causes of uncertainty in the simulation of the tropical climate (Li et al., 2006). Cox et al. (2004 and 2000) highlighted how, on the one hand, General Circulation Models and ESMs tend to underestimate precipitation in the Amazon; on the other hand, how the projected decreasing trends, in combination with the feedbacks from the tropical biome, are likely to cause a catastrophic future scenario. The HadCM3-LC IPCC-AR4 model, in a business as usual scenario, projected the almost complete dieback of the Amazon forest (Cox et al., 2004). The introduction of the new generation of ESMs, in particular the new generation of the Hadley Center models (HadGem2-ES) used for this study, produced slightly more optimistic projections but confirmed the possibility of Amazon forest dieback toward the end of the 21st century. These results were recently confirmed by two studies based on the feedback between decreasing precipitation and forest productivity in the Amazon (Hilker et al., 2014; Longo et al., 2018; Zhang et al., 2015). The inclusion of a sensitivity analysis running the model using inputs form the wet IPSL-CM5 and the dry GISS-E2 allowed to quantify the range of uncertainty related to the choice of the climate projections.

Our results confirm the dominant trends of climate change in the hydrological cycle of a subregion of the Amazon: climate change, in both moderate and severe scenarios, is expected to not only reduce peak flows in both rainy and dry seasons in the Tapajós River basin but also delay the beginning of the rainy season and reduce its duration. These trends were also identified for the historical period (Marengo et al., 2018; Paiva et al., 2013*;* Sorribas et al., 2016), while drier conditions in line with the results illustrated in this study were projected for the eastern Amazon using an ensemble of five CMIP5 model outputs (Sorribas et al., 2016). The impact of climate change on the Tapajós River network in Sorribas et al. *(*2016*)* is in line with our findings. In our study, considering only climate change, as land use is not considered in Sorribas et al. (2016), the flow reduction could be quantified in about 10–20% for low and middle flows and about 5–20% for the high and very high discharge values by the period 2025–2045, being 20–50% and 5–20%, respectively, in the period 2079–2099 in Sorribas et al. (2016), results that are compatible considering the difference in the time scale. It has to be taken into account that, however, the high degree of uncertainty linked to the climate projections, as shown above, might affect the results of this and other studies, especially for the high and very high flows.

In general, deforestation is expected to have a less dominant trend in terms of impacts on river flows in the Tapajós. In line with the existing literature on this topic (Von Randow et al., 2019; Guimberteau et al., 2017; Stickler et al., 2013; Brown et al., 2005; Andréassian, 2004; Sahin & Hall, 1996; Bruijnzeel, 1990; Bosch & Hewlett, 1982), we found that land use change has opposing effects on streamflow compared to the decreasing trends caused by climate change and also acts to increase variability in streamflows. These results are consistent with the data collected during the experiments conducted in the neighboring Xingu basin (Dias et al., 2015; Hayhoe et al., 2011; Stickler et al., 2013). In particular, Dias et al. (2015) found that in the small catchments they analyzed, the conversion of forested land to soybean production brought an average increase in discharge of almost 100%. The effect of climate change is projected to be, at least partially and in the short term, offset by the effect of deforestation, which by reducing ET increases the runoff in the water balance equation. Our results considering both climate and land use change are in line with a similar study by Guimberteau et al. (2017), which, by using more conservative deforestation scenarios (Aguiar et al., 2016) in combination with previous generation CMIP3 climate projections, found a climate-driven reduction of Tapajós discharge of about 31% by 2100, partially offset by an increase of about 27% in case of the most Extreme Deforestation change.

It is important to highlight that the simulations conducted for our study do not incorporate vegetation-climate feedbacks at the local scale, which would have probably dampened, at least in part, the direct effects of deforestation (Swann et al., 2015; Zhang et al., 2015). In fact, simplifying the complex forest-rainfall interactions (Spracklen et al., 2018), deforestation directly affects the evapotranspiration, which in turn

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contributes in determining the amount of precipitation in the area (van der Ent et al., 2010; van der Ent & Savenije, 2011). In addition, the difference between the land use scenarios used in our modeling setup and the ones used for the setup of the ESM models for the CMIP5 climate projections could have brought some degree of inconsistency in this analysis that was not possible to be quantified, as discussed in section 2.3. This problem, however, is common to all the other studies that tried to quantify the separate impacts of climate and land use change in future scenarios.

As mentioned above, climate change is expected to affect the basin relatively uniformly, with slightly different degrees of sensitivity between the larger and the smaller subbasins. The impact of deforestation, however, is more evident in the Eastern part of the basin, especially in the headwaters. The relatively high sensitivity of the Upper, Lower Teles Pires, and Jamanxim, with respect to the other subbasins, is likely to be linked with the topographic characteristics of the specific areas. Moreover, as discussed in Arias et al. (2018), the relatively low water accumulation of these hydrological units means that impacts of environmental changes on flows are more evident. Subbasins characterized by higher flows and larger contributing areas (like Lower Juruena, Upper, and Lower Tapajós), in fact, are likely to be more resilient to climate and land use changes, at least until the tipping point in deforestation, when rainfall begins to be affected, is reached.

Our findings provide timely information about the future development of the area that could be relevant for policy makers. Brazil is planning to extensively exploit this basin for hydropower production, with the possible construction of more than 40 large (>30 MW) dams (MME & EPE, 2015). Due to the specific topography of the basin, almost all the plants planned for the Tapajós, Jamanxim, Juruena, and Teles Pires subbasins are designed as run-of-the-river (with limited or no storage capacity). The lack of storage makes the hydropower production completely dependent on daily to weekly river flows, with very little or no possibility to buffer the seasonal and subseasonal variability (IEA, 2013). The overall reduction of river flows, jointly with the shift and the shortening of the wet season, could seriously impact the productivity of the planned hydropower system (Stickler et al., 2013). Moreover, the climate patterns in the southern part of the basin are expected to impact the agricultural sector, the main economic resource of this area. The possible decline in the rainfed agricultural productivity driven by climate change could push the farmers to invest in adaptation strategies that could include irrigation. This would further increase the anthropogenic pressure on the river flows and represent a competitive water demand for the energy sector.

5. Summary and Conclusions

In this study we used the land surface model ED2 integrated with a routing scheme (ED2+R) to analyze future hydrological alterations caused by two main environmental changes, climate and land use, in a large basin of the Brazilian Amazon, the Tapajós. Land surface models are powerful tools to study hydrological dynamics under changing climate and land use conditions. Their ability to reconstruct the water balance, taking into consideration fine-scale climate dynamics and annual land cover transitions, makes them powerful instruments for hydrological simulations. In order to translate the results of the land surface simulations in terms of river flows, the simulated water fluxes were processed using a hydrological routing scheme. We used the integrated model ED2+R to simulate different combinations of climate and land use change disturbances for the period 2026–2045, comparing the results with respect to a baseline scenario shaped on the climate and land use of the period 1986–2005. We analyzed the hydrological alterations caused by climate change simulating the land surface dynamics by forcing our land surface model with two global climate scenarios estimated by the ESM HadGem2-ES. The uncertainty linked with the climate projections was evaluated by analyzing simulations computed using two additional ESMs (IPSL-CM5 and GISS-E2). Human disturbances on land use were simulated using two scenarios with two different degrees of deforestation, a moderate and an extreme.

Our results show that the two environmental drivers are expected to affect the regional streamflows in ways similar to what experimental studies have found so far. Climate change is expected to generally reduce the river flows in the basin throughout the year, bringing a considerable delay in the flow seasonality and increasing the overall variability. Future climate scenarios, both moderate (RCP 4.5) and severe (RCP 8.5) are likely to cause a decline in river flows throughout the year and cause a substantial delay in the beginning of the wet season and a reduction in its duration. Land use change (deforestation and conversion to agriculture), conversely, is expected to cause an increase in flow magnitude as well as interannual and intraannual variability; however, the delay in the beginning of the wet season and a reduction in its duration occurring under future climate scenarios were also evident in the scenarios combining climate and land use change. Beside the environmental consequences and the impacts on the ecosystem services, these findings have important implications for the management and development of water resources in the Amazon. Brazil's strategic energy agenda heavily relies on hydropower development in the Amazon area: a substantial decrease of river discharges and a shift in flow seasonality might compromise the complex interactions among the complementary sources of electricity in the country's energy mix, threatening in that way its energy security. The abovementioned dynamics might be also impacted by the increasing pressure of agricultural and mining activities in the area. Therefore, further research assessing the impacts of hydrological change on water-based socioeconomic sectors has to be considered crucial for the sustainable development of the region. In addition, further analyses could address some of the limitations, in particular related to the possible inconsistencies linked to the climate projections and the bias correction methodology used, which might affect the results of this study. Fully integrated climate-dynamic and vegetation-hydrology simulations could provide more information about the feedback between deforestation and precipitation patterns, both locally and in the downwind regions. This could be particularly important considering that, according to van der Ent et al. (2010), about 70% of the water resources flowing in the highly populated and economically vital southeastern Brazil depend on the evaporation from the Amazon. The availability of bias-corrected climate projections, with a level of details suitable for these models, could be extremely useful to efficiently generate more accurate water availability scenarios vital for the strategical planning of long-term infrastructural investments. This is particularly true in the case of the flow-dependent run-of-the-river hydropower technology, the only viable hydropower alternative for relatively flat areas as in the case of the Brazilian Amazon.

Author Contribution

F. F., P. R. M., and J. B. designed the study; F. F., M. E. A., and E. L. carried out the analysis; F. F., M. E. A., and P. R. M. wrote the paper. F. F. P., A. L., and M. L. provided feedback on the analysis and final document.

Conflicts of Interest

The authors declare no conflict of interest.

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