



# 1 Technical Note: A hydrological routing scheme for the

- 2 Ecosystem Demography model (ED2+R)
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# 17 Abstract

18 Land surface models are excellent tools for studying how climate change and land use affect 19 surface hydrology. However, in order to assess the impacts of earth processes on river flows, 20 simulated changes in runoff need to be routed through the landscape using a hydrological 21 transport scheme. In this Technical Note we describe the integration of the Ecosystem 22 Demography (ED2) model with a hydrological routing scheme. ED2 is a terrestrial biosphere 23 model capable of incorporating sub-grid scale ecosystem heterogeneity arising from land-use 24 change, making it ideally suited for investigating combined impacts of changes in climate, 25 atmospheric carbon dioxide concentrations, and land-cover on the water cycle. The resulting 26 ED2+R model calculates the lateral propagation of surface and subsurface runoff resulting from 27 the terrestrial biosphere models' vertical water balance in order to determine spatio-temporal 28 patterns of river flows within the simulated region. We evaluated the ED2+R model in the





Tapajós, a large river basin in southeastern Amazonia, Brazil. The results showed that the
integration of ED2 with the lateral routing scheme substantially improves the ability of the
model to reproduce daily to decadal river flow dynamics in the Tapajós.

4

#### 5 1 Introduction

6 Understanding the impacts of deforestation (e.g., Lejeune et al. 2015; Medvigy et al. 2011; 7 Andréassian 2004) and climate change (e.g., Jiménez-Cisneros et al. 2014) on the earth's water 8 cycle has been a topic of substantial interest in recent years because of potential serious 9 implications to ecosystems and society (e.g., Wohl et al. 2012; Brown et al., 2005). Analyses 10 of impacts of climate change on the earth's water cycle are increasingly using terrestrial 11 biosphere models, which are capable of estimating changes in the vertical water balance (i.e., 12 evapotranspiration, soil moisture, deep percolation, surface and sub-surface runoff) as a 13 function of climate forcing and and/or land-use induced changes in canopy structure and 14 composition (Zulkafli et al. 2013).

15 Terrestrial biosphere models can mechanistically represent the multiple interactions among 16 land-surface energy balance, the hydrological cycle, and the carbon cycle that occur in 17 terrestrial ecosystems. Examples of terrestrial biosphere models actively used for hydrological 18 and earth systems sciences include: the Joint UK Land Environment Simulator (JULES) (Best 19 et al. 2011; Clark et al. 2011); the Community Land Model (CLM) (Lawrence et al. 2011; 20 Oleson et al. 2010); the Lund-Potsdam-Jena (LPJ) land model (Gerten et al. 2004; Sitch et al. 21 2003); the Max Plank Institute MPI-JSBACH model (Vamborg et al. 2011; Raddatz et al. 22 2007); and the Integrated Biosphere Simulator (IBIS) (Kucharik et al. 2000).

23 Initial formulations of the hydrological processes within terrestrial biosphere models were 24 based on simple "bucket" model formulations (Cox et al. 1999 after Carson 1982). Moisture 25 within each climatological grid cell of the domain was simulated in a single below-ground pool 26 in which surface temperature and specific soil moisture factors determined evaporation, while 27 runoff was equal to the bucket overflow (Cox et al. 1999; Carson 1982). Since that formulation, 28 the hydrologic schemes within terrestrial biosphere models have become increasingly 29 sophisticated. In the most recent generation of land surface models, water fluxes in and out of 30 the soil column are vertically-resolved and take into account feedbacks among the different 31 components, for instance, through an explicit formulation of the soil-plant-atmosphere 32 continuum that allows a better representation of the interactions between evapotranspiration,





1 soil moisture and runoff (Clark et al. 2015). In this way, terrestrial biosphere models can 2 estimate the temporal and spatial distribution of water resources across the simulated domain 3 under changing climate and land cover conditions. The accurate computation of the vertical 4 water balance, however, is only part of the process of estimation of river flows, which are vital 5 data for water resource management (e.g. flood control, hydropower, irrigation). To calculate 6 river flows from a land surface model that could be compared with actual river gauge 7 observations, water runoff must be routed through the studied landscape, considering the 8 topographic and geomorphological features that control water flow (Arora et al. 1999). 9 Consequently, terrestrial biosphere models have been integrated with routing schemes. For 10 example, JULES has been integrated with the Total Runoff Integrating Pathways (TRIP) (Oki 11 et al. 2001; Oki et al. 1999); LPJ with the routing scheme described in Rost et al. (2008); CLM 12 with the Variable Infiltration Capacity's river routing model (Liang et al. 1994); MPI-JSBACH 13 with the Hydrological Discharge (MPI-HD) model (Hagemann & Gates 2001; Hagemann & 14 Dumenil 1997); and IBIS with the river transport model THMB (Coe et al. 2008).

15 Similar to the models mentioned above, the Ecosystem Demography (ED2) is a terrestrial 16 biosphere model that simulates the coupled water, carbon, and energy dynamics of terrestrial 17 land surfaces (Longo 2014; Medvigy et al. 2009; Moorcroft et al. 2001). One of the key benefits 18 of ED2's formal approach to scaling vegetation dynamics is its ability to describe, in a 19 physically consistent manner, the coupled water, carbon and energy dynamics of heterogeneous 20 landscapes (Hurtt et al. 2013; Medvigy et al. 2009; Moorcroft et al. 2001). ED2's ability to 21 incorporate sub-grid scale ecosystem heterogeneity arising from land-use change means that 22 the model is ideally suited for investigating of how the combined impacts of changes in climate, 23 atmospheric carbon dioxide concentrations, and land-cover are affecting terrestrial ecosystems. 24 For example, ED2 was successfully used to simulate the carbon flux dynamics in the North 25 American continent (Hurtt et al. 2002; Albani et al. 2006), and to assess the impacts on 26 Amazonian ecosystems of changes in climate, atmospheric carbon dioxide and land use (Zhang 27 et al. 2015). Moreover, ED2, coupled with a regional atmospheric circulation component, has been also successfully applied to assess the impacts of deforestation on the Amazonian climate 28 29 (Knox et al. 2015; Swann et al. 2015). ED2 is a unique tool to evaluate impacts from global and 30 regional changes on ecosystem function, and therefore, it could provide critical information for 31 hydrological studies. In this technical note, we describe the integration of ED2 with a flow 32 routing scheme. This exercise is aimed at calculating the lateral propagation and attenuation of 33 the surface and subsurface runoff resulting from the vertical balance calculations, reproducing





in this way river flows through a large basin. The advantage of the proposed model is the ability
 to better predict the sensitivity of river flows to global and regional environmental changes,
 combining the advantages of biosphere and hydrological models, bringing together global,
 regional, and local scale hydrological dynamics in a single modelling framework. The product
 obtained from this exercise was tested in the Tapajós basin, a large river system in southeastern
 Amazonia, Brazil.

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## 8 2 Ecosystem Demography (ED2) model

9 ED2 is a biosphere simulation model capable of representing biological and physical processes 10 driving the dynamics of ecosystems using climate and soil properties. It is unique amongst 11 terrestrial biosphere models because, rather than using a conventional "ecosystem as big-leaf" 12 assumption, ED2 is formulated at the scale of individual plants. The resulting ecosystem-scale 13 dynamics and fluxes are then calculated through a formal scaling procedure that accurately 14 captures the resulting macroscopic behavior of the ecosystem within each climatological gridcell. It simulates ecosystem structure and dynamics as well as the corresponding carbon, energy, 15 16 and water fluxes (Figure 1; Hurtt et al. 2013; Medvigy et al. 2009; Moorcroft et al. 2001). ED2 17 simulates the dynamics of different plant functional types subdivided into tiles with a 18 homogeneous canopy (Swann et al. 2015; Medvigy et al. 2009). Generally, plant functional 19 types are represented by: early successional trees (fast growing, low wood density, and water-20 needy); mid-successional trees; late-successional trees (slow growing, shade tolerant, high 21 wood density); and C4 grasses (comprising also pasture and agriculture) (Swann et al. 2015; 22 Medvigy et al. 2009). Each grid cell is subdivided into a series of dynamic tiles that represent 23 the sub-grid scale heterogeneity within each cell. The size of the grid cell is determined by the 24 resolution of meteorological forcing and soil characteristics data, typical from 1 degree to 1 km. 25 This characteristic of the ED2 model makes it suitable for a more realistic simulation of regions 26 characterized by a mixture of natural and anthropogenically-modified landscapes. ED2 27 simulates biosphere dynamics taking into consideration natural disturbances, such as forest fires and plant mortality due to changing environmental conditions, as well as human-caused 28 29 disturbances, such as deforestation and forest harvesting (Medvigy et al. 2009; Albani et al. 30 2006). Disturbances are expressed in the model as annual transitions between primary 31 vegetation, secondary vegetation, and agriculture (cropland and pasture) (Albani et al. 2006). 32 Natural disturbance, such as wildfire, is represented in the model by the transition from primary





1 vegetation (forest in the case of the Amazon) to grassland-shrubland, and subsequently to 2 secondary vegetation (forest re-growth); the abandonment of an agricultural area is represented 3 with the conversion from grassland to secondary vegetation, while forest logging is represented 4 by the transition from primary or secondary vegetation to grassland. The model is composed of 5 several modules operating at multiple temporal and spatial scales, including plant mortality, 6 plant growth, phenology, biodiversity, soil biogeochemistry, disturbance, and hydrology 7 (Longo 2014; Medvigy et al. 2009). For a more complete description of the model, we refer the 8 reader to the literature available (Zhang et al. 2015; Longo 2014; Medvigy et al. 2009; 9 Moorcroft et al. 2001). In this section, we describe in further detail the hydrological sub-10 component, most related to the topic of this specific study. The hydrological module of the ED2 11 model is derived from the Land Ecosystem-Atmospheric Feedback model (LEAF-2) (Walko et 12 al. 2000). The model computes the water cycle through the vegetation, air-canopy space, and 13 soils, which results in daily estimates of subsurface and surface runoff from each grid cell, 14 isolated from the others in the domain. The number of soil layers and their thickness influence 15 the accuracy with which the model is able to represent the gradients near the surface. Hydraulic conductivity of the soil layers is a function of soil texture and moisture (Longo 2014). 16 17 Groundwater exchange is a function of hydraulic conductivity, soil temperature and terrain 18 topography. Water percolation is limited to the bottom layer by the subsurface drainage, 19 determining the bottom boundary conditions. A more detailed description of the hydrological 20 sub-component of the ED2 model is available in Longo (2014).

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## 22 3 ED2 runoff routing scheme (ED2+R)

23 Daily runoff estimates from ED2 were computed for specific grid cells independently; therefore 24 a hydrological routing scheme was linked to this model in order to estimate flow attenuation 25 and accumulation as water moves through the landscape towards the basin outlet. The flow 26 routing scheme chosen was adapted from the IPH-MGB, a rainfall-runoff model that has been 27 extensively used in large river basins in South America (Collischonn et al. 2007). The original IPH-MGB model is composed of four different sub-models: soil water balance, 28 29 evapotranspiration, intra-cell flow propagation, and inter-cell routing through the river network. 30 Only the latter two sub-models were utilized as the processes accounted for by the first two are 31 estimated with ED2. The resulting ED2+R model computes the daily total volume of water 32 passing through any given grid cell in the resulting drainage network in two separate steps:





1 First, ED2 estimates of daily surface and subsurface runoff from each grid cell are divided into 2 three linear reservoirs with different residence times to represent overland flow (surface 3 reservoir), interflow (intermediate reservoir) and groundwater flow (base reservoir) (Figure 2). The reservoirs are used to determine the contribution and attenuation of river flow by different 4 5 soil layers, characterized by different propagation times. The sum of overland flow, interflow, 6 and groundwater flow is then moved from each grid cell into the drainage network computed 7 from a digital elevation model (DEM) using the COTAT (Cell Outlet Tracing with an Area 8 Threshold) algorithm (Reed 2003) and is enhanced with a parameter that accurately assigns 9 flow directions to DEM grid cells over regions with meandering rivers (Annex A). Each DEM 10 grid cell therefore becomes part of a flow path which then accumulates water to a final 11 downstream drainage network outlet (Figure 3 - Panel b). A complete description of the 12 technique for defining drainage networks from DEMs employed in this study can be found in 13 Paz et al. (2006).

14 Once water reaches the drainage network, ED2+R solves the Muskingum-Cunge equation of 15 flow routing using a finite-difference method as a function of river length, width, height and 16 roughness as well as terrain elevation slope (Collischonn et al. 2007; Reed 2003). Statistical 17 relationships for the river morphology were obtained as a function of the drainage area based 18 on geomorphic data collected by Brazil's National Water Agency (ANA) and the Observation 19 Service for the geodynamical, hydrological and biogeochemical control of erosion/alteration 20 and material transport in the Amazon basin (HyBAM) at several gauging stations in the Amazon 21 and Tocantins basins as presented by Coe et al. (2008). Later on, further studies successfully 22 employed these statistical relationships to estimate river geometric parameters to carry out 23 hydrodynamic simulations of the Amazon River system (Paiva et al., 2013; Paiva et al., 2011). 24 Multiple groups of grid cells with common hydrological features, or hydrological response 25 units, can be created in order to parameterize and calibrate ED2+R. In our approach, 26 hydrological traits associated with soil and land cover are primarily computed in ED2, thus we 27 calibrated ED2+R at the subbasin level as delineated considering the DEM. Details about the 28 calibration procedure are provided in the next section.

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## 30 4 Parameterization and evaluation for the Tapajós river basin application

We parameterized and evaluated the ED2+R formulation for the Tapajós River Basin, one of
 the largest tributaries of the Amazon. For calibration purposes the basin was divided into seven





1 sub-basins, each of them with a corresponding gauge for which historical daily river flow 2 observations were available (Panel a in Figure 3). Simulations were carried out for the period 3 1970-2008. The ED2 model was forced using reconstructed climate (Sheffield et al. 2006) and 4 land use/land cover data (Hurtt et al. 2006; Soares-Filho et al. 2006) at 1-degree spatial 5 resolution. The original meteorological dataset has a 3-hour temporal resolution, which was 6 downscaled to an hourly resolution, as described in Zhang et al. (2015). Surface and subsurface 7 runoff calculated for each cell with ED2 are connected with the three linear reservoirs of the 8 routing scheme (Figure 2).

9 Model Calibration: The ED2+R model was manually calibrated through a two-step procedure 10 using gauge observations (HYBAM and ANA) spanning a period of 17 years, from 1976 to 11 1992 (the period 1970-1975 was not considered in order to avoid simulation initiation effects). 12 In the first step, the flow partitioning between the original ED2 surface and subsurface 13 reservoirs and the ED2+R surface, intermediate, and base reservoirs (parameters  $\alpha$  and  $\beta$  in 14 Figure 2) were adjusted. Following the methodology described by Anderson (2002), the 15 sensitivity of the  $\alpha$  and  $\beta$  parameters was tested by running the model multiple times (>30). For 16 each run, the goodness-of-fit was quantified comparing the results of the simulation to historical 17 flow observations. The combination of the  $\alpha$  and  $\beta$  parameters characterized by the highest 18 goodness-of-fit was selected. Parameters  $\alpha$  and  $\beta$  were assumed to be uniform for the whole 19 basin. In the second step, the residence times ( $\tau$ ) of flow within the ED2+R reservoirs of each 20 grid cell in the domain were calibrated (CS, CI, and CB in Figure 2). The calibration procedure 21 characterizing the second step is similar to the previous one but in this case the calibration is 22 repeated for each subbasin sequentially; the calibration process was conducted from the furthest 23 upstream subbasins - headwaters - to the final outlet of the basin (Anderson 2002). The model 24 was run multiple times (between 30 and 50 per subbasin) with different combinations of the 25 three parameters (CS, CI, and CB in Figure 2); for each run, the goodness-of-fit was quantified. 26 This allowed us to design a sensitivity curve of the model to different combinations of the three 27 parameters for each of the seven subbasins, and to select the combination that best approaches the historical observations. Missing observations in the river flow records were filled via linear 28 29 spatial and temporal interpolation between the series in neighboring gauge stations (Equation 30 1):

32 
$$Obs_{\gamma}(t) = K + \beta_1 \cdot Obs_z(t) + \beta_2 \cdot Obs_q(t) + \beta_3 \cdot Obs_{\gamma}(t - 365) + \beta_4 \cdot Obs_{\gamma}(t + 365)$$
 (1)





1

2 Where z, y, and q are three gauge stations with timeseries highly correlated (Pearson's  $r \ge 0.85$ ),

3 and t expresses time in days. The estimated  $\beta$  coefficients were used for the estimation of the

4 missing observations in the site y. For further details on the calibration procedure, see Appendix

5 B.

The period 1993-2008 was used for model evaluation. Comparison between observations and
simulated flows (goodness-of-fit) were carried out using Pearson's R correlation coefficient
(Pearson 1895), volume ratio, and the Nash-Sutcliffe (NSE) coefficient (Nash & Sutcliffe 1970)
(Figure 4).

10

## 11 5 Results

12 The integration of the routing scheme with ED2 substantially increases the ability of the model 13 to accurately reproduce the observed temporal variations in river flows at the basin outlet 14 (Figure 5). This statement applies to all of the sub-basins, as the application of the routing 15 scheme substantially improved the goodness-of-fit between simulated and observed values with 16 respect to all three measures, Nash-Sutcliffe (NSE) (Figure 4, panel a), Pearson's R correlation 17 coefficient (panel b in Figure 4), and volume ratio (panel c in Figure 4). Both routed (ED2+R) 18 and non-routed (ED2) simulation results manage to reproduce reasonably well the observed 19 water availability in the basin in terms of volume (panel c in Figure 4); however, the application 20 of the routing scheme improves the ability of the model to reproduce the spatio-temporal 21 propagation of water flows across the basin (panels a and b in Figure 4, and Figure 6). The 22 model's performance in simulating river flows is generally higher in the downstream sub-basins 23 and poorer in the headwaters; in the Upper Teles Pires and Upper Juruena, the model achieved 24 the lowest NSE, and although water volumes are reproduced reasonably well, the seasonal 25 variability is less accurate. The NSE and correlation values increased substantially in the central 26 and lower part of the basin (Figure 4 and Figure 6). The Jamanxim basin results, especially 27 during the validation period, are affected by the very short and fragmented observation time 28 series.

29 Flow duration curves, representing the probability of the flow values to exceed a specific value,

30 highlight the substantial improvement of the model results after applying the routing scheme

31 (Figure 6). The simulated flow duration curves show an excellent match to the observations in





the furthest upstream sub-basins, especially in the cases of the Upper Juruena and Upper Teles
 Pires (panels a and b in Figure 6). For downstream subbasins, Lower Juruena and Lower Teles
 Pires, flood duration curves show a general tendency of overestimating the lowest values of the
 distribution (panels c to g in Figure 6). This is also evident in the multiyear hydrograph (Figure
 5), which shows that the ED2+R tend to overestimate the observations during the dry seasons
 of the period under consideration.

7

## 8 6 Discussion

9 As the results in Figures 4-6 show, the integration of ED2 with a simple one-way routing 10 scheme substantially increases the model's ability to reproduce daily water flows through a 11 large river basin. The results highlight the ability of the ED2+R model to more accurately 12 capture the hydrological dynamics in the study domain in terms of both volumes (Figure 6) and 13 seasonality of river flows (Figure 5). As seen in Figure 6, the performance of the model in 14 simulating river flows in the basin is generally higher in the downstream sub-basins and poorer in the headwaters. This is due to both the relatively coarse spatial resolution of the model in 15 16 combination with the limitations typical of most land surface models in capturing the 17 interactions with the deep groundwater (Lobligeois et al. 2014; Zulkafli et al. 2013; Smith et al. 18 2004). The combined effect of groundwater interactions and spatial resolution is more evident 19 in the upstream part of the basin because of the greater marginal contribution of baseflow in 20 these areas. Further downstream, the effect of groundwater interactions and spatial resolution 21 is masked by the larger rainfall-runoff contribution and the overall flow accumulation from the 22 upstream subbasins. Other recent hydrological simulations of the Tapajós have obtained higher 23 accuracy (e.g. Mohor et al. 2015; Collischonn et al. 2008; Coe et al. 2008); however, these 24 simulations were set up discretizing the basin into a finer spatial resolution grid (9 to 20 km 25 versus 55 km grid cells).

The principal advantage of the ED2+R model is the ability to better predict the sensitivity of the river flows to global environmental changes. As mentioned earlier, ED2+R combines the advantages of biosphere and hydrological models, bringing together global, regional, and local scale hydrological dynamics in a single modelling framework. This can be used to study how different hydrological systems are being affected by changes in climate forcing and changes in ecosystem composition and structure arising from the combination of: changes in climate, rising atmospheric carbon dioxide, and land-transformation.





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## 2 7 Conclusions

3 Biosphere models are excellent tools to study hydrological dynamics under climate and land 4 use/land cover changing conditions. These models are usually set to simulate long periods in 5 large regions, usually at global or continental scales. Their ability in reconstructing the water 6 balance at relatively fine geographical and temporal resolution, taking into consideration global 7 environmental changes makes them powerful instruments for hydrological simulations. In order 8 to translate the results of the land surface simulation in terms of river flows, the simulated 9 results need to be processed using a hydrological routing scheme. In this Technical Note, we 10 present the integration of the terrestrial biosphere model Ecosystem Demography 2 (ED2) with 11 the Muskingum-Cunge routing scheme. We tested the integrated model (ED2+R) in the Tapajós 12 river basin, a large tributary of the Amazon in Brazil, for the period 1970-2008. The results 13 showed that the integration of a biosphere model with a routing scheme substantially improves 14 the ability of the land surface simulation to reproduce the hydrological and river flow dynamics 15 at the basin scale. The main limitations highlighted in this case study were linked to the 16 relatively coarse spatial resolution of the model and the rough representation of groundwater 17 flow typical of this kind of models. Moreover, the terrestrial biosphere model ED2 and the 18 routing scheme are presented here in a one-way integration. The full coupling of the routing 19 scheme and ED2 could further improve the ability to reproduce the water balance considering 20 flooded ecosystems, a feature that could be extremely important especially in the simulation of 21 environments like the tropical forest, where local evapotranspiration plays a primary role in the 22 specific ecosystem's dynamics. Future efforts will be oriented towards the resolution of the highlighted limitations and current research is focusing on the application of ED2+R on 23 24 understanding historical changes and future projections of the impacts of climate change and 25 deforestation on the Amazon's water resources.

26

## 27 Annex A – COTAT algorithm

28 Cell outlet tracing with an area threshold (COTAT) algorithm (retrieved from Reed et al. 2003):

29 "The basic rules for the COTAT algorithm are defined here:

- 30 1. Identify an outlet pixel in each coarse-resolution cell. The outlet pixel drains the largest
- 31 *cumulative area of any pixel in that cell.*





- 1 2. For each cell, trace downstream, from its outlet pixel, along the flow path defined by the
- 2 high-resolution flow directions.
- 3 3. For each subsequent outlet pixel reached, determine its total drainage area and subtract the
- 4 *drainage area of the starting outlet pixel.*
- 5 *Case 1: If this difference is greater than a user specified area threshold, stop tracing.*
- 6 Case 2: Otherwise, continue tracing to subsequent outlets until either the area threshold is
- 7 *exceeded or until the edge of the high-resolution grid is reached.*
- 8 4. Assign the flow direction of the starting cell toward the neighboring cell with the farthest
- 9 outlet along the trace defined in steps 2 and 3" (from Reed et al. 2003 Section 3. Methodology,
- 10 page 2)
- 11

## 12 Annex B – Calibration of the ED2+R model for the Tapajós River Basin

13 In this annex, we present the calibration of the ED2+R model for the Tapajós river basin. The 14 calibration process has two steps, as highlighted in Figure 2. The first step is the partitioning of 15 the flows from the two reservoirs of the ED2 biosphere model to the three reservoirs of the 16 ED2+R routed biosphere model. The second step regards the adjustment of the residence times 17 of the water flows in the three reservoirs for each of the grid cells in each of the subbasins (overland, intermediate, and groundwater flows - CS, CI, CB in Figure 2). Figure B.1 shows 18 19 the different combinations of the  $\alpha$  and  $\beta$  parameters introduced in Figure 2. The color bar 20 indicates the Nash-Sutcliffe indicator (NSE) resulting from the comparison between the 21 simulated and observed river flow values obtained using different combinations of the 22 parameters  $\alpha$  (x axis) and  $\beta$  (y axis). The chosen combination (indicated by an x in Figure B.1) 23 lies in one of the optimal combination areas (NSE  $\sim 0.8$ ).

The second step of calibration is represented by the adjustment of residence time of the overland, intermediate, and groundwater flows (CS, CI, and CB in Figure 2). Figure B.2 shows how the model is sensitive to marginal variation in initial conditions of baseflow, particularly in the upstream section (i.e. UTP - Upper Teles Pires, UJ – Upper Juruena, and LTP – Lower Teles Pires). Changes in initial groundwater contributions in the downstream part of the basin are almost completely uninfluential for the overall representation of the river flows (i.e. UT and LT - Upper and Lower Tapajós).





Figure B.3 describes instead the calibration of the residence time for each of the subbasins. The
different combinations of the values assigned to the parameters CS, CI, and CB significantly
impact the overall goodness-of-fit of the river flow simulations (NSE indicator). The calibration
process was conducted from the furthest upstream subbasins – headwaters – (UTP – Upper
Teles Pires, UJ – Upper Juruena, and JA – Jamanxim) to the final outlet of the basin (LT –
Lower Tapajós). The different combinations are marked with the corresponding NSE value; the
optimal combination is marked in red (Figure B.3).

8

## 9 Author's contribution

10 F. Pereira, P. Moorcroft and J. Briscoe designed the study; F. Pereira developed the model code;

F. Farinosi, M. Arias, and E. Lee carried out the analysis; F. Farinosi, M. Arias and P. Moorcroft
wrote the paper.

13

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#### 24 References

- 25 Albani, M., Medvigy, D., Hurtt, G. C. and Moorcroft, P. R.: The contributions of land-use
- 26 change, CO 2 fertilization, and climate variability to the Eastern US carbon sink, Glob.
- 27 Chang. Biol., 12(12), 2370–2390, doi:10.1111/j.1365-2486.2006.01254.x, 2006.
- 28 Anderson, E. A.: Calibration of Conceptual Models for Use in River Forecasting. [online]
- 29 Available from: http://www.nws.noaa.gov/oh/hrl/calb/calibration1102/main.htm, 2002.





- 1 Andréassian, V.: Waters and forests: from historical controversy to scientific debate, J.
- 2 Hydrol., 291(1-2), 1–27, doi:10.1016/j.jhydrol.2003.12.015, 2004.
- 3 Arora, V. K., Chiew, F. H. S. and Grayson, R. B.: A river flow routing scheme for general
- 4 circulation models, J. Geophys. Res., 104(D12), 14347, doi:10.1029/1999JD900200, 1999.
- 5 Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., Essery, R. . L. H., Ménard, C. B.,
- 6 Edwards, J. M., Hendry, M. A., Porson, A., Gedney, N., Mercado, L. M., Sitch, S., Blyth, E.,
- 7 Boucher, O., Cox, P. M., Grimmond, C. S. B. and Harding, R. J.: The Joint UK Land
- 8 Environment Simulator (JULES), model description Part 1: Energy and water fluxes,
- 9 Geosci. Model Dev., 4(3), 677–699, doi:10.5194/gmd-4-677-2011, 2011.
- 10 Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W. and Vertessy, R. A.: A review of
- 11 paired catchment studies for determining changes in water yield resulting from alterations in
- 12 vegetation, J. Hydrol., 310(1-4), 28–61, doi:10.1016/j.jhydrol.2004.12.010, 2005.
- 13 Carson, D.: Current parametrisations of land-surface processes in atmospheric general
- 14 circulation models, in Land surface processes in atmospheric general circulation models,
- 15 edited by P. Eagleson, Cambridge University Press, Cambridge, UK., 1982.
- 16 Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., Pryor, M.,
- 17 Rooney, G. G., Essery, R. L. H., Blyth, E., Boucher, O., Harding, R. J., Huntingford, C. and
- 18 Cox, P. M.: The Joint UK Land Environment Simulator (JULES), model description Part 2:
- 19 Carbon fluxes and vegetation dynamics, Geosci. Model Dev., 4(3), 701–722,
- 20 doi:10.5194/gmd-4-701-2011, 2011.
- 21 Clark, M. P., Fan, Y., Lawrence, D. M., Adam, J. C., Bolster, D., Gochis, D. J., Hooper, R. P.,
- 22 Kumar, M., Leung, L. R., Mackay, D. S., Maxwell, R. M., Shen, C., Swenson, S. C. and
- 23 Zeng, X.: Improving the representation of hydrologic processes in Earth System Models,
- 24 Water Resour. Res., 51(8), 5929–5956, doi:10.1002/2015WR017096, 2015.
- 25 Coe, M. T., Costa, M. H. and Howard, E. A.: Simulating the surface waters of the Amazon
- 26 River basin: impacts of new river geomorphic and flow parameterizations, Hydrol. Process.,
- 27 22(14), 2542–2553, doi:10.1002/hyp.6850, 2008.
- 28 Collischonn, B., Collischonn, W. and Tucci, C. E. M.: Daily hydrological modeling in the
- 29 Amazon basin using TRMM rainfall estimates, J. Hydrol., 360(1-4), 207–216,
- 30 doi:10.1016/j.jhydrol.2008.07.032, 2008.





- 1 Collischonn, W., Allasia, D., Da Silva, B. C. and Tucci, C. E. M.: The MGB-IPH model for
- 2 large-scale rainfall—runoff modelling, Hydrol. Sci. J., 52(5), 878–895,
- 3 doi:10.1623/hysj.52.5.878, 2007.
- 4 Cox, P. M., Betts, R. A., Bunton, C. B., Essery, R. L. H., Rowntree, P. R. and Smith, J.: The
- 5 impact of new land surface physics on the GCM simulation of climate and climate sensitivity,
- 6 Clim. Dyn., 15(3), 183–203, doi:10.1007/s003820050276, 1999.
- 7 Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W. and Sitch, S.: Terrestrial vegetation and
- 8 water balance-hydrological evaluation of a dynamic global vegetation model, J. Hydrol.,
- 9 286(1-4), 249–270, doi:10.1016/j.jhydrol.2003.09.029, 2004.
- 10 Hagemann, S. and Dumenil, L.: A parametrization of the lateral waterflow for the global
- 11 scale, Clim. Dyn., 14(1), 17–31, doi:10.1007/s003820050205, 1997.
- 12 Hagemann, S. and Gates, L. D.: Validation of the hydrological cycle of ECMWF and NCEP
- 13 reanalyses using the MPI hydrological discharge model, J. Geophys. Res., 106(D2), 1503,
- 14 doi:10.1029/2000JD900568, 2001.
- 15 Hurtt, G. C., Pacala, S. W., Moorcroft, P. R., Caspersen, J., Shevliakova, E., Houghton, R. A.
- and Moore, B.: Projecting the future of the U.S. carbon sink, Proc. Natl. Acad. Sci., 99(3),
- 17 1389–1394, doi:10.1073/pnas.012249999, 2002.
- 18 Hurtt, G. C., Frolking, S., Fearon, M. G., Moore, B., Shevliakova, E., MALYSHEV, S.,
- 19 PACALA, S. W. and Houghton, R. A.: The underpinnings of land-use history: three centuries
- 20 of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands,
- 21 Glob. Chang. Biol., 12(7), 1208–1229, doi:10.1111/j.1365-2486.2006.01150.x, 2006.
- 22 Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P.,
- 23 Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein
- 24 Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P.,
- 25 van Vuuren, D. P. and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500-
- 26 2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting
- 27 secondary lands, Clim. Change, 109(1), 117–161, doi:10.1007/s10584-011-0153-2, 2011.
- 28 Hurtt, G. C., Moorcroft, P. R. and Pacala, S. W.: Ecosystem Demography Model: Scaling
- 29 Vegetation Dynamics Across South America, Ecosyst. Demogr. Model Scaling Veg. Dyn.
- 30 Across South Am. Model Prod. [online] Available from:
- 31 http://daac.ornl.gov/MODELS/guides/EDM\_SA\_Vegetation.html, 2013.





- 1 Jiménez-Cisneros, B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., Jiang, T.
- 2 and Mwakalila, S. S.: Freshwater resources., in Climate Change 2014: Impacts, Adaptation,
- 3 and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to
- 4 the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by C.
- 5 B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M.
- 6 Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S.
- 7 MacCracken, P. R. Mastrandrea, and L. L. White, pp. 229–269., Cambridge University Press,
- 8 ambridge, United Kingdom and New York, NY, USA. [online] Available from: https://ipcc-
- 9 wg2.gov/AR5/images/uploads/WGIIAR5-Chap3\_FINAL.pdf, 2014.
- 10 Knox, R. G., Longo, M., Swann, A. L. S., Zhang, K., Levine, N. M., Moorcroft, P. R. and
- 11 Bras, R. L.: Hydrometeorological effects of historical land-conversion in an ecosystem-
- 12 atmosphere model of Northern South America, Hydrol. Earth Syst. Sci., 19(1), 241–273,
- 13 doi:10.5194/hess-19-241-2015, 2015.
- 14 Kucharik, C. J., Foley, J. A., Delire, C., Fisher, V. A., Coe, M. T., Lenters, J. D., Young-
- 15 Molling, C., Ramankutty, N., Norman, J. M. and Gower, S. T.: Testing the performance of a
- 16 dynamic global ecosystem model: Water balance, carbon balance, and vegetation structure,
- 17 Global Biogeochem. Cycles, 14(3), 795–825, doi:10.1029/1999GB001138, 2000.
- 18 Lawrence, D. M., Oleson, K. W., Flanner, M. G., Thornton, P. E., Swenson, S. C., Lawrence,
- 19 P. J., Zeng, X., Yang, Z.-L., Levis, S., Sakaguchi, K., Bonan, G. B. and Slater, A. G.:
- 20 Parameterization improvements and functional and structural advances in Version 4 of the
- 21 Community Land Model, J. Adv. Model. Earth Syst., 3(3), M03001,
- 22 doi:10.1029/2011MS000045, 2011.
- 23 Lejeune, Q., Davin, E. L., Guillod, B. P. and Seneviratne, S. I.: Influence of Amazonian
- 24 deforestation on the future evolution of regional surface fluxes, circulation, surface
- 25 temperature and precipitation, Clim. Dyn., 44(9-10), 2769–2786, doi:10.1007/s00382-014-
- 26 2203-8, 2015.
- 27 Liang, X., Lettenmaier, D. P., Wood, E. F. and Burges, S. J.: A simple hydrologically based
- 28 model of land surface water and energy fluxes for general circulation model, J. Geophys.
- 29 Res., 99(D7), 14,415–14,428, 1994.
- 30 Lobligeois, F., Andréassian, V., Perrin, C., Tabary, P. and Loumagne, C.: When does higher
- 31 spatial resolution rainfall information improve streamflow simulation? An evaluation using





- 1 3620 flood events, Hydrol. Earth Syst. Sci., 18(2), 575–594, doi:10.5194/hess-18-575-2014,
- 2 2014.
- 3 Longo, M.: Amazon Forest Response to Changes in Rainfall Regime: Results from an
- 4 Individual-Based Dynamic Vegetation Model, Harvard University. [online] Available from:
- 5 http://dash.harvard.edu/handle/1/11744438, 2014.
- 6 Medvigy, D., Wofsy, S. C., Munger, J. W., Hollinger, D. Y. and Moorcroft, P. R.:
- 7 Mechanistic scaling of ecosystem function and dynamics in space and time: Ecosystem
- 8 Demography model version 2, J. Geophys. Res. Biogeosciences, 114(G1), G01002,
- 9 doi:10.1029/2008JG000812, 2009.
- 10 Medvigy, D., Walko, R. L. and Avissar, R.: Effects of Deforestation on Spatiotemporal
- 11 Distributions of Precipitation in South America, J. Clim., 24(8), 2147–2163,
- 12 doi:10.1175/2010JCLI3882.1, 2011.
- 13 Mohor, G. S., Rodriguez, D. A., Tomasella, J. and Siqueira Júnior, J. L.: Exploratory analyses
- 14 for the assessment of climate change impacts on the energy production in an Amazon run-of-
- 15 river hydropower plant, J. Hydrol. Reg. Stud., 4, 41–59, doi:10.1016/j.ejrh.2015.04.003,
- 16 2015.
- 17 Moorcroft, P. R., Hurtt, G. C. and Pacala, S. W.: A method for scaling vegetation dynamics:
- 18 The ecosystem demography model (ED), Ecol. Monogr., 71(4), 557–586, doi:10.1890/0012-
- 19 9615(2001)071[0557:AMFSVD]2.0.CO;2, 2001.
- 20 Nash, E. and Sutcliffe, V.: River flow forecasting Through conceptual models PART I- A
- 21 Discussion of principles, J. Hydrol., 10, 282–290, 1970.
- 22 Oki, T., Nishimura, T. and Dirmeyer, P.: Assessment of Annual Runoff from Land Surface
- 23 Models Using Total Runoff Integrating Pathways (TRIP), J. Meteorol. Soc. Japan, 77(1B),
- 24 235–255 [online] Available from:
- 25 https://www.jstage.jst.go.jp/article/jmsj1965/77/1B/77\_1B\_235/\_article, 1999.
- 26 Oki, T., Agata, Y., Kanae, S., Saruhashi, T., Yang, D. and Musiake, K.: Global assessment of
- 27 current water resources using total runoff integrating pathways, Hydrol. Sci. J., 46(6), 983-
- 28 995, doi:10.1080/02626660109492890, 2001.
- 29 Oleson, K. W., Lawrence, D. M., Bonan, G. B., Flanner, M. G., Kluzek, E., Lawrence, P. J.,
- 30 Levis, S., Swenson, S. C. and Thornton, P. E.: Technical Description of version 4.0 of the





- 1 Community Land Model (CLM), Boulder, CO USA. [online] Available from:
- 2 http://www.cesm.ucar.edu/models/cesm1.0/clm/CLM4\_Tech\_Note.pdf, 2010.
- 3 Paiva, R. C. D., Collischonn, W. and Tucci, C. E. M.: Large scale hydrologic and
- 4 hydrodynamic modeling using limited data and a GIS based approach, J. Hydrol., 406(3-4),
- 5 170–181, doi:10.1016/j.jhydrol.2011.06.007, 2011.
- 6 Paiva, R. C. D., Collischonn, W. and Buarque, D. C.: Validation of a full hydrodynamic
- 7 model for large-scale hydrologic modelling in the Amazon, Hydrol. Process., 27(3), 333–346,
- 8 doi:10.1002/hyp.8425, 2013.
- 9 Paz, A. R., Collischonn, W. and Lopes da Silveira, A. L.: Improvements in large-scale
- 10 drainage networks derived from digital elevation models, Water Resour. Res., 42(8),
- 11 doi:10.1029/2005WR004544, 2006.
- 12 Pearson, K.: Note on regression and inheritance in the case of two parents, Proc. R. Soc.
- 13 London, 58, 1895.
- 14 Raddatz, T. J., Reick, C. H., Knorr, W., Kattge, J., Roeckner, E., Schnur, R., Schnitzler, K.-
- 15 G., Wetzel, P. and Jungclaus, J.: Will the tropical land biosphere dominate the climate-carbon
- 16 cycle feedback during the twenty-first century?, Clim. Dyn., 29(6), 565–574,
- 17 doi:10.1007/s00382-007-0247-8, 2007.
- 18 Reed, S. M.: Deriving flow directions for coarse-resolution (1-4 km) gridded hydrologic
- 19 modeling, Water Resour. Res., 39(9), doi:10.1029/2003WR001989, 2003.
- 20 Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J. and Schaphoff, S.: Agricultural
- 21 green and blue water consumption and its influence on the global water system, Water
- 22 Resour. Res., 44(9), doi:10.1029/2007WR006331, 2008.
- 23 Sheffield, J., Goteti, G. and Wood, E. F.: Development of a 50-Year High-Resolution Global
- 24 Dataset of Meteorological Forcings for Land Surface Modeling, J. Clim., 19(13), 3088–3111,
- 25 doi:10.1175/JCLI3790.1, 2006.
- 26 Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O.,
- 27 Levis, S., Lucht, W., Sykes, M. T., Thonicke, K. and Venevsky, S.: Evaluation of ecosystem
- 28 dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global
- 29 vegetation model, Glob. Chang. Biol., 9(2), 161–185, doi:10.1046/j.1365-2486.2003.00569.x,
- 30 2003.





- 1 Smith, M. B., Koren, V. I., Zhang, Z., Reed, S. M., Pan, J.-J. and Moreda, F.: Runoff response
- 2 to spatial variability in precipitation: an analysis of observed data, J. Hydrol., 298(1-4), 267-
- 3 286, doi:10.1016/j.jhydrol.2004.03.039, 2004.
- 4 Soares-Filho, B. S., Nepstad, D. C., Curran, L. M., Cerqueira, G. C., Garcia, R. A., Ramos, C.
- 5 A., Voll, E., McDonald, A., Lefebvre, P. and Schlesinger, P.: Modelling conservation in the
- 6 Amazon basin., Nature, 440(7083), 520–3, doi:10.1038/nature04389, 2006.
- 7 Swann, A. L. S., Longo, M., Knox, R. G., Lee, E. and Moorcroft, P. R.: Future deforestation
- 8 in the Amazon and consequences for South American climate, Agric. For. Meteorol., 214-
- 9 215, 12–24, doi:10.1016/j.agrformet.2015.07.006, 2015.
- 10 Vamborg, F. S. E., Brovkin, V. and Claussen, M.: The effect of a dynamic background albedo
- scheme on Sahel/Sahara precipitation during the mid-Holocene, Clim. Past, 7(1), 117–131,
- 12 doi:10.5194/cp-7-117-2011, 2011.
- 13 Walko, R. L., Band, L. E., Baron, J., Kittel, T. G. F., Lammers, R., Lee, T. J., Ojima, D.,
- 14 Pielke, R. A., Taylor, C., Tague, C., Tremback, C. J. and Vidale, P. L.: Coupled Atmosphere-
- 15 Biophysics–Hydrology Models for Environmental Modeling, J. Appl. Meteorol., 39(6), 931–
- 16 944, doi:10.1175/1520-0450(2000)039<0931:CABHMF>2.0.CO;2, 2000.
- 17 Wohl, E., Barros, A., Brunsell, N., Chappell, N. A., Coe, M., Giambelluca, T., Goldsmith, S.,
- 18 Harmon, R., Hendrickx, J. M. H., Juvik, J., McDonnell, J. and Ogden, F.: The hydrology of
- 19 the humid tropics, Nat. Clim. Chang., 2(9), 655–662, doi:10.1038/nclimate1556, 2012.
- 20 Zhang, K., de Almeida Castanho, A. D., Galbraith, D. R., Moghim, S., Levine, N. M., Bras,
- 21 R. L., Coe, M. T., Costa, M. H., Malhi, Y., Longo, M., Knox, R. G., McKnight, S., Wang, J.
- 22 and Moorcroft, P. R.: The fate of Amazonian ecosystems over the coming century arising
- 23 from changes in climate, atmospheric CO2, and land use, Glob. Chang. Biol., 21(7), 2569-
- 24 2587, doi:10.1111/gcb.12903, 2015.
- 25 Zulkafli, Z., Buytaert, W., Onof, C., Lavado, W. and Guyot, J. L.: A critical assessment of the
- 26 JULES land surface model hydrology for humid tropical environments, Hydrol. Earth Syst.
- 27 Sci., 17(3), 1113–1132, doi:10.5194/hess-17-1113-2013, 2013.
- 28





# 1 Figures



2

Figure 1. Schematic of the enthalpy fluxes (all arrows) and water fluxes (all but solid black
arrows) that are solved in ED2. The schematic is based on Walko et al. (2000); and Medvigy et
al. (2009). (Courtesy of Marcos Longo).

6

7



8

Figure 2. Schematic representation of the connection between the terrestrial biosphere model and the hydrological routing scheme. Calibrating parameters circled in red (Figure B.1 and Figure B.3). The reservoirs are used to determine the contribution of streamflow that comes from overland flow (surface reservoir), interflow (intermediate reservoir) and groundwater flow (base reservoir). The daily sum of these three reservoirs is then moved from each grid cell into

<sup>14</sup> the drainage network.







- 2 Figure 3. (a) Organization of the Tapajós basin into seven sub-basins: Upper Juruena (UJ);
- 3 Lower Juruena (LJ); Upper Teles Pires (UTP); Lower Teles Pires (LTP); Jamanxim (JA); Upper
- 4 Tapajós (UT); and Lower Tapajós (LT). (b) ED2+R represents the domain in grid cells with
- 5  $0.5^{\circ}$  resolution (~ 55 km). The black segments indicate flow accumulation network.







1 Figure 4. Calibration and validation results. (a) Nash-Sutcliffe, (b) Pearson's R, and (c) volume 2 ratio, optimal values = 1; in red ED2+R results, in blue ED2. Filled bars corresponds to

<sup>3</sup> calibration period, shaded bars for validation period.









Figure 5. Calibration and validation of the river flow (m<sup>3</sup>/sec) at Itaituba (farthest downstream
river gauge – Lower Tapajós sub-basin). ED2 output (green line), ED2+R (red line), and
Observations (blue dotted line). The dotted black line splits the calibration and validation
periods.



Figure 6. Flow duration curves (percentage of time that flow  $- m^3/s$  – is likely to equal or exceed determined thresholds) of observed values (blue), ED2 outputs (green), ED2+R (red) at the outlet of the seven sub-basins. (a) Upper Juruena (UJ); (b) Upper Teles Pires (UTP); (c) Lower





- 1 Juruena (LJ); (d) Lower Teles Pires (LTP); (e) Upper Tapajós (UT); (f) Jamanxim (JA); and
- 2 (g) Lower Tapajós (LT).
- 3



4

Figure B.1. Calibration of flow partitioning (parameters alpha and beta in Figure 2) between
the ED2 and the ED2+R reservoirs. Color bar indicates the NSE values of the simulated versus
the observed river flow values (0 very different, 1 very similar)





Figure B.2. Initial conditions of baseflow sensitivity for different ED2+R subbasins in the
 domain. Upper Juruena (UJ); Upper Teles Pires (UTP); Lower Juruena (LJ); Lower Teles Pires
 (LTP); Upper Tapajós (UT); Jamanxim (JA); and Lower Tapajós (LT).

















Figure B.3. Calibration of the residence times (τ) of the flow within the ED2+R reservoirs of
 different grid cells in the domain. Overland, intermediate and groundwater flows are indicated
 respectively by CS, CI, and CB (Figure 2). In red the chosen combination. (a) Upper Juruena
 (UJ); (b) Upper Teles Pires (UTP); (c) Lower Juruena (LJ); (d) Lower Teles Pires (LTP); (e)
 Upper Tapajós (UT); (f) Jamanxim (JA); and (g) Lower Tapajós (LT).