Supplementary material

Accounting for spatial variation in vegetation properties improves simulations of Amazon forest biomass and productivity in a global vegetation model

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A. Sensitivity Analyses Model Configuration Setup

In order to quantify the response of IBIS to spatially varying parameters based on observed data we performed series of sensitivity analyses (Table A). We performed a suite of basin-wide simulations (SA1 to SA7) that systematically test the sensitivity of the model to each of the parameters analyzed (Table A). These simulations are: soil texture (SA1); soil depth (SA2); carbon allocation to wood, leaf and roots (SA3); woody biomass residence time (SA4); maximum carboxylation capacity Rubisco (SA5); specific leaf area index (SA6); stomatal conductance coefficient (SA7). In these tests, constant parameter values (minimum and maximum found in field measurement) are assigned based on the literature (Table A), the model is run for the entire Amazon basin, and the results are compared to the output from the CA simulation. From these simulations we learn which parameters can be expected to most affect model NPP_w and AGB_w outcomes.

A.1. Soil Texture

Soil texture data is based on the IGBP-DIS global soil and Quesada et al., (2010) dataset in the control simulation (CA), while for the sensitivity analyses simulations (SA1) the soil texture is considered homogeneous for the entire basin and it is set to a value of 33% clay and 47% of sand.

A.2. Soil Depth

The soil depth is considered homogeneous with 10 m for (CA) control simulation and 4 m for the soil sensitivity analyses simulation (SA2). There are 6 soil layers with thicknesses from the top layer to the bottom of 0.25, 0.375, 0.625, 1.25, 2.5, 5 m and 0.1, 0.15, 0.25, 0.5, 1 and 2 m, respectively for 10 m and 4 m depths.

A.3. Carbon allocation in tropical broadleaf trees

The partitioning of the carbon allocation to woods, leaves and roots in a tropical broadleaf tree has been considered invariant in space and time in most numerical models (Malhi et al., 2011). In the IBIS control simulation (CA) the carbon allocation to wood is set at 50%, 30% to leaves and 20% to roots. The original assumption of the model allocating 50% of carbon to wood is in the upper limit of the observed range of carbon allocation (25-50%, Malhi et al., (2011)). Therefore to test the sensitivity of IBIS AGB_w and

NPP_w, the carbon allocation fraction is varied (Table A). In SA3 the allocation is set to the minimum value observed from field data with 25%, 33%, 42%, for wood, leaves and roots respectively.

A.4. Woody biomass residence time in tropical broadleaf trees

The residence time of wood in tropical broadleaf trees is considered to be on average 25 yr, in the control simulation (CA) where it is fixed in time and space. Field data show that the residence time can vary from 25 years up to 100 years in Amazonia forest broadleaf trees in different locations (Phillips et al., 2004). The sensitivity test (SA4) assumes 100 yr homogeneous residence time for entire basin.

A.5. Maximum carboxylation capacity of Rubisco in tropical broadleaf trees

The maximum carboxylation capacity of Rubisco activity (V_{cmax}) is a critical photosynthetic parameter in the model. Observed values range from 40 to 75 $\mu molCO_2/m^2/s$ (Mercado et al., 2009; Mercado et al., 2011; Domingues et al., 2005). The control simulation (CA) uses a V_{cmax} for tropical broadleaf trees set at 75 $\mu molCO_2/m^2/s$. The sensitivity analyses (SA5) is performed with the lower limit observed from field data fixed at 40 $\mu molCO_2/m^2/s$.

A.6. Specific leaf area index in tropical broadleaf trees

The specific leaf area is also an important photosynthetic parameter in the model, describing the area available for photosynthetic activity. The control simulation (CA) uses a fixed value of 25 m^2/kg, which is the upper limit observed from field data (Fyllas et al., 2009). The sensitivity test (SA6) is set to the minimum value of 16 m^2/kg observed in the field.

A.7. Stomatal Conductance Coefficient

The stomatal conductance is also an important component of the photosynthetic process. Its computation relies on the predefined stomatal conductance coefficient (m), the slope of the regression between stomatal conductance and photosynthesis, that is not well characterized in space from field data. The values used were based on model calibrations, Rocha et al., (1996). To better understand the model sensitivity to this coefficient it is defined as 11 and fixed in space in the control simulation (CA). For the sensitivity analyses it is fixed at 7 (SA7). All other properties such as, heat capacity of upper canopy, leaf reflectance, orientation of upper canopy leaves, are less characterized in a spatial resolution and are of minor effect over the productivity and biomass of the system.

Table A: Summary of the parameterization setup for each of the simulation experiments: the control simulation (CA) with the original IBIS prescribed homogeneous parameterization; the group of sensitivity simulations (from SA1 to SA7) with homogeneous parameterizations in space.

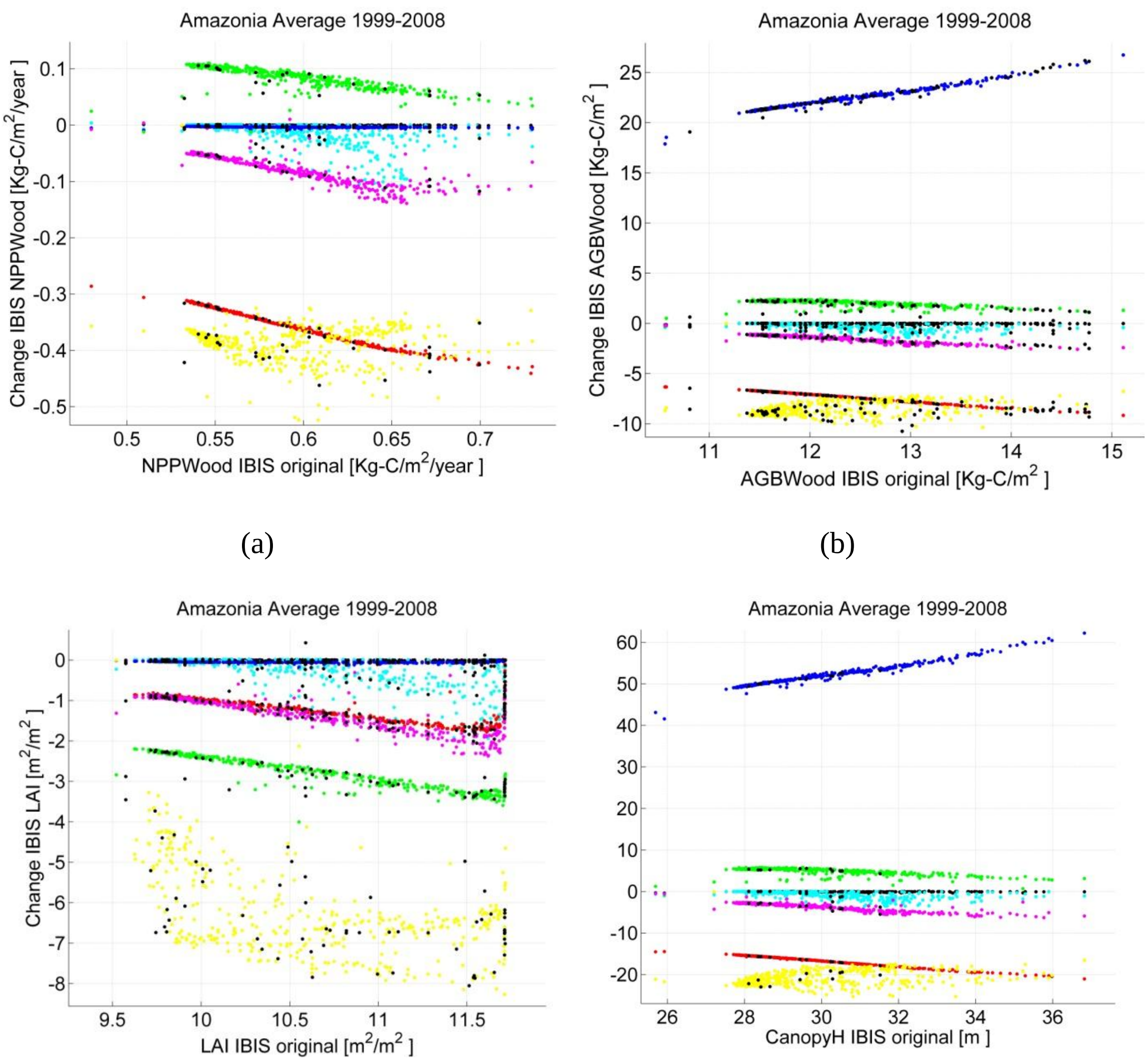
	Homogeneous Parameterization	
Unit	(CA) Control Simulation	(SA#) Sensitivity Simulation

Soil Texture	%	Map IGBP-DIS + Quesada et al., 2010	**(SA1)** Fixed space 33%clay 47%sand
Soil Depth	m	Fixed space 10	**(SA2)** Fixed space 4
Carbon Allocation to wood, leaves and roots	%	Fixed space 50%Wood 30%Leaves 20%Roots	**(SA3)** Fixed space 25%Wood 33%Leaves 42%Roots
Woody Biomass Residence Time	years	Fixed space 25	**(SA4)** Fixed space 100
Maximum carboxylation capacity of Rubisco (V_{cmax})	μmol $CO_2/m^2/s$	Fixed space 75	**(SA5)** Fixed space 40
Specific Leaf Area Index (SLA)	m^2/kg	Fixed space 25	**(SA6)** Fixed space 16
Stomatal Conductance Coefficient		Fixed space 11	**(SA 7)** Fixed space 7

B. Results: Sensitivity Analyses

In this section the results of the IBIS sensitivity simulations (SA1 to SA7) are presented with the goal of identifying the most potential properties contributing to the simulated spatial variability of productivity and biomass in the Amazonian Forest. We investigate the effect of different, climatological, soil and biophysical properties including: soil texture (SA1), soil depth (SA2), carbon allocation to wood, leaves and roots (SA3), woody biomass residence time (SA4), maximum carboxylation capacity of Rubisco (V_{cmax}) (SA5), specific leaf area index (SA6), and stomatal conductance coefficient (SA7) (Table A). We make a comparison of each SA# to the reference CA simulation where modeled NPP_w is subtracted from the control simulation CA (SA#-CA). The same analyses are performed for each of the output properties (Fig. B) of woody net primary productivity

(NPP_w) and woody above ground biomass (AGB_w), leaf area index (LAI) and canopy height. Their sensitivities are calculated as the percent change of increase or decrease in NPP_w (or AGB_w, LAI or canopy height) in one cell ([(SA# - CA) / CA] * 100 %) as shown in Table B.



(a) (b)

(c) (d)

Figure B: above ground woody net primary productivity (NPP_w) (a), woody above ground productivity (AGB_w) (b), leaf area index (LAI) (c), canopy height (d). The change of each of the properties is given for each of the sensitivity experiments (SA#) minus control experiment (CA) (SA#-CA) described in Table A: soil texture (in orange, SA1), soil depth (light blue, SA2), wood carbon allocation (in red, SA3), wood residence time (in dark blue, SA4), V_{cmax} (in yellow, SA5), SLA (in green, SA6), and stomatal conductance coefficient (in magenta, SA7). The black dots represent the pixels where there are field observations for NPP_w, AGB_w, LAI and canopy height. Each point in the figure represents a $1^o x 1^o$ pixel in the Amazon tropical forest basin that has a specific local climate and soil texture, and represents an average of 10 years from 1999-2008.

Table B: Result of the sensitivity analyses of each of the simulation exercises (from SA1 to SA7) described in Table A, the range of sensitivity imposed for each one is listed in the second column. The percentage change from the control (SA1-SA7) of NPP_w, AGB_w, LAI, and canopy height are shown ([(SA# - CA) / CA] * 100 %). Changes greater than 60% are shaded, and the greatest change of each variable is in bold.

Parameter	**Change in Homogeneous Parameters (from CA to SA#)**	**NPP wood**	**AGB wood**	**LAI**	**Canopy Height**
Climate	Extreme Variability	35%	45%	30%	30%

SA1	Soil Texture	-	Decrease <1%	Decrease <1%	Decrease <1%	Decrease <1%
SA2	Soil Depth	From 10 to 4 m	Decrease <10%	Decrease <10%	Decrease <10%	Decrease <10%
SA3	Carbon Allocation to wood, leaves and roots	From 50% to25% Wood; From 30% to 33% Leaves; From 20% to 42% Roots	Decrease 60%	Decrease 60%	Decrease 10-15%	Decrease 55%
SA4	Woody Biomass Residence Time	From 25 to 100 yr	Decrease <1%	**Increase <180%**	Decrease <1%	**Increase <170%**
SA5	Maximum carboxylation capacity of Rubisco (V_{cmax})	From 75 to 40 μmol $CO_2/m^2/s$	**Decrease 60-80%**	Decrease 60-80%	**Decrease 40-70%**	Decrease 60-80%
SA6	Specific Leaf Area Index (SLA)	From 25 to 16 m^2/kg	Increase <20%	Increase <20%	Decrease 20-30%	Increase <20%
SA7	Stomatal Conductance Coefficient	From 11 to 7	Decrease <20%	Decrease <20%	Decrease 10-20%	Decrease 10-20%

B.1. Above ground woody net primary productivity (NPP_w)

Field observations show an about 260% spatial variability of woody biomass primary productivity in Amazon forests (Malhi et al., 2004). This large variability cannot be explained by the direct effect of climate and soil alone and vegetation models generally fail to reproduce the NPP_w variability across the Amazonian because of constant parameterizations. In this section we explore the individual sensitivity of NPP_w to each of the properties listed in Table A (from SA1 to SA7). This simplified exercise, in which the parameters are systematically altered but remain spatially constant, allows us to identify the parameters in the model with the greatest potential to explain the observed spatial variability of NPP_w (Fig. B, Table B).

IBIS simulated NPP_w is more sensitive to the variability of the Rubisco enzyme (V_{cmax}) than to any of the other parameters analyzed (Fig. B, Table B). A change in V_{cmax} from 75 (CA) to 40 $\mu molCO_2/m^2/s$ (SA5) changes the NPP_w from about 60-80% depending on the climate scenarios (Table B). The prescribed reduction in V_{cmax} causes a decrease in the wood productivity, predominantly from an increase in autotrophic respiration, which is larger than the increase in gross primary productivity. This higher sensitivity of V_{cmax} may clarify our understanding of the contribution of soil fertility in explaining the observed spatial variability of NPP_w.

The second most important factor affecting simulated NPP_w is the carbon allocation (Table B, SA3). The change in carbon allocation to wood from 50% (CA) to 25% (SA3) imparts a variation in NPP_w of up to 60%. The third most important factor affecting simulated NPP_w is the direct effect of climate. Climate variations within the basin alone account for 35% of simulated variability in NPP_w. The inherent variation in the observed specific leaf area index (SLA) as tested (SA6) and stomatal conductance coefficient (SA7), results in a simulated NPP_w variability of as much as 20%.

Changing soil depth from 10 m (CA) to 4 m (SA2) imparts as much as 10% variation in simulated NPP_w across the sites of measurements (black dots over light blue,

Fig. B), however it can be as large as 20% in other places in the Amazon basin where water availability is limited (light blue, Fig. B). The greatest effect is in regions where the water availability is limited, such as southeastern Amazonia where the water availability drops to 60% or below during the dry season. In most of the forest sites where the wood productivity has been measured and our comparisons are made the water availability is greater than 80% most of the year, as a result, the soil depth effect on NPP_w is much less than 10% in those locations. If the soil moisture of 80% that we simulate in most of the Amazon forest is realistic, then soil depth may not be a significant factor explaining the observed high variability of the woody biomass productivity. However if the soil water stress is higher than predicted then the soil depth assumption could be an important factor. Therefore, soil depth could become a key factor in areas that present reduced water availability or in drought events where potential water availability is lower than 60%.

The contributions of the other components (SA4 and SA1) to NPP_w such as woody biomass residence time and soil texture are less than 1%. In summary the simulated results are most sensitive to variability of V_{cmax}, which suggests that knowledge of the spatial variation of V_{cmax} is essential to understand the observed NPP_w spatial variability.

B.2. Woody above ground biomass

The spatial variability of the observed woody above ground biomass in the Amazon forest is about 120% (Malhi et al., 2006), which cannot be explained by the direct effect of climate and or soil properties alone. In this section we explore the individual sensitivity of AGB_w to each properties listed in Table A. This exercise allows us to identify the variables with the potential to explain part or total AGB_w spatial variability observed from field measurements (Fig. B, Table B).

Woody residence time, of all of the parameters tested (Table B, SA4), most affects the simulated woody above ground biomass. A change in woody residence time from 25 years (CA) to 100 years (SA4) increases simulated AGB_w by 15 to 40 kg C/m^2 depending on the climate associated. This range in woody residence time corresponds to an AGB_w variability of 180%. AGB variability due to V_{cmax} and carbon allocation was 60 to 80% (V_{cmax}, SA5) and 60% (carbon allocation, SA3).

The climate variability effect on AGB can be observed from the variability of AGB in the x axis in Fig. Bb, where each point represents a pixel in the Amazon basin under its corresponding climate. The climate causes a 45% change in the simulated AGB_w. Specific leaf area index (SA6) and stomatal conductance (SA7) cause a change in AGB_w of up to 20% each. Changing soil depth from 10 to 4 m results in less than 10% (SA2) change in regions where water availability is lower than 80%. Other properties tested (SA1) cause AGB_w changes of less than 1%. In summary, woody biomass residence time variation of 25-100 years is the variable with the greatest influence on the simulated AGB_w which suggests that knowledge of the spatial variation of woody residence time is essential to understand the observed AGB_w spatial variability.

B.3. Leaf Area Index and canopy height

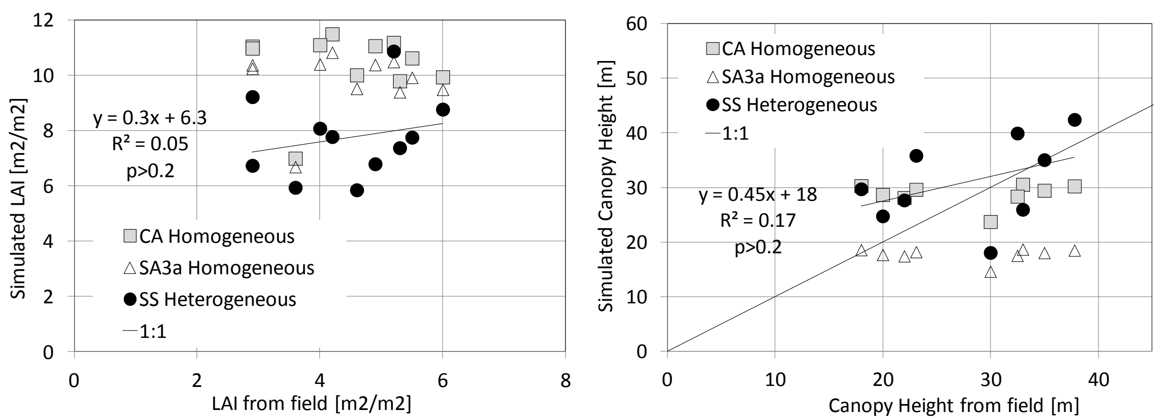
The spatial variability of the observed leaf area index and canopy height in the Amazon forest are about 100%. In this section we explore the individual sensitivity of leaf area index and canopy height to each properties listed in Table 2. This exercise allows us to identify the variables with the potential to explain part or all of the observed spatial variability (Fig. B, Table B).

The properties that most affect the leaf area index are V_{cmax} (40-70%, SA3) followed by the specific leaf area index (SLA) (20-30 %, SA6). The leaf area index is defined as a function of biomass of leaves and SLA. As there is a high sensitivity of productivity to V_{cmax} this is reflected in the total biomass of leaves (because leaf turnover is constant) and so on LAI. The effect of carbon allocation (10-15%) is relatively small due to the low variability of the carbon allocated to leaves in these simulations. Field data in the Amazon basin suggests that carbon allocation to leaves is mostly invariant and is about 30% (Malhi et al., 2011).

The canopy height sensitivity follows a similar pattern to the above ground biomass. It is most affected by the woody biomass residence time (170%, SA4), followed by the V_{cmax} (60-80%, SA5) and carbon allocation (55%, SA3).

C. Results: Leaf Area Index and Canopy Height comparison to field data

The simulated leaf area index and canopy height are qualitatively improved compared to observations when heterogeneous parameterizations are included SS (Fig. C). The overall correlations are low and they are not significantly correlated ($p<0.05$). However small improvement in some sites is noticed when the heterogeneous parameterizations are considered instead of the homogeneous ones (Fig. C). The properties that most improve the simluated LAI are the V_{cmax} and the SLA, as expected from the sensitivity analyses (black dot, Fig. Ca). Even after the improvement in the heterogeinity of the properties the LAI simulations are still in general overestimating the observed values. This overestimation may be related to the interactions between biophysical responses to increasing CO_2. With increasing CO_2, the magnitude of the carbon going to all pools increases. Because turnover and allometry do not change in time, the carbon is allocated evenly to the stem, leaves, and roots pools. As a result the LAI must increase with increasing CO_2. In reality, it is likely that leaf turnover rates may increase and allometry may vary in time thereby damping the effects on LAI (Körner 2009).



(a) (b)

Figure C: Comparison between IBIS simulated and field data, LAI (a) and Canopy Height (b). Final simulation with heterogeneous parameterization (SS, black circle); homogeneous parameterization with woody carbon allocation fix 34% (SA3a, triangles); and control simulation original homogeneous parameterizations (CA, gray square).

D. Analyses of observed data outliers

The spatial location of the site series of data analyzed is presented in Fig. D1 and the outliers are briefly discussed. The outliers are being discussed because we believe they are part of some inconsistency between field measurements and or in the parameterization data methodology. The site level simulation (SS) of NPP_w and AGB_w reproduced in general the spatial pattern observed from field data (Fig. 6 a,b) with higher productivity in the west and higher woody biomass in central Amazonia (Fig. D1 a,b). The difference between simulated and observed NPP_w (Fig. D1 c,d) explicitly shows the location of the main divergences.

The observed NPP_w data of three of the main outliers, JEN (Jenaro, Peru), CAQ (Caqueta, Colombia), and SCR (San Carlos de Rio Negro, Venezuela) have a distinctly different relationship with air temperature than the other sites (Fig. D2). These sites were classified as having low confidence level in NPP_w estimation (Malhi et al., 2004). Therefore, the unexpected behavior of these three sites could be an artifact of the field data estimates. The other outlier is CUZ (Cuzco Amazonico, Peru). The site level measurement shows a high fraction phosphorous that results in a high estimated V_{cmax} and therefore high NPP_w. The reason for this is result of the methodology adopted to estimate the V_{cmax}. As it is a linear regression of soil total P and as we do not consider a saturation of V_{cmax} to high P content there is a clear overestimation of CUZ site V_{cmax} and as a consequence in the simulated NPP_w. These outlier sites were removed from the statistical analyses to avoid undesirable interference.

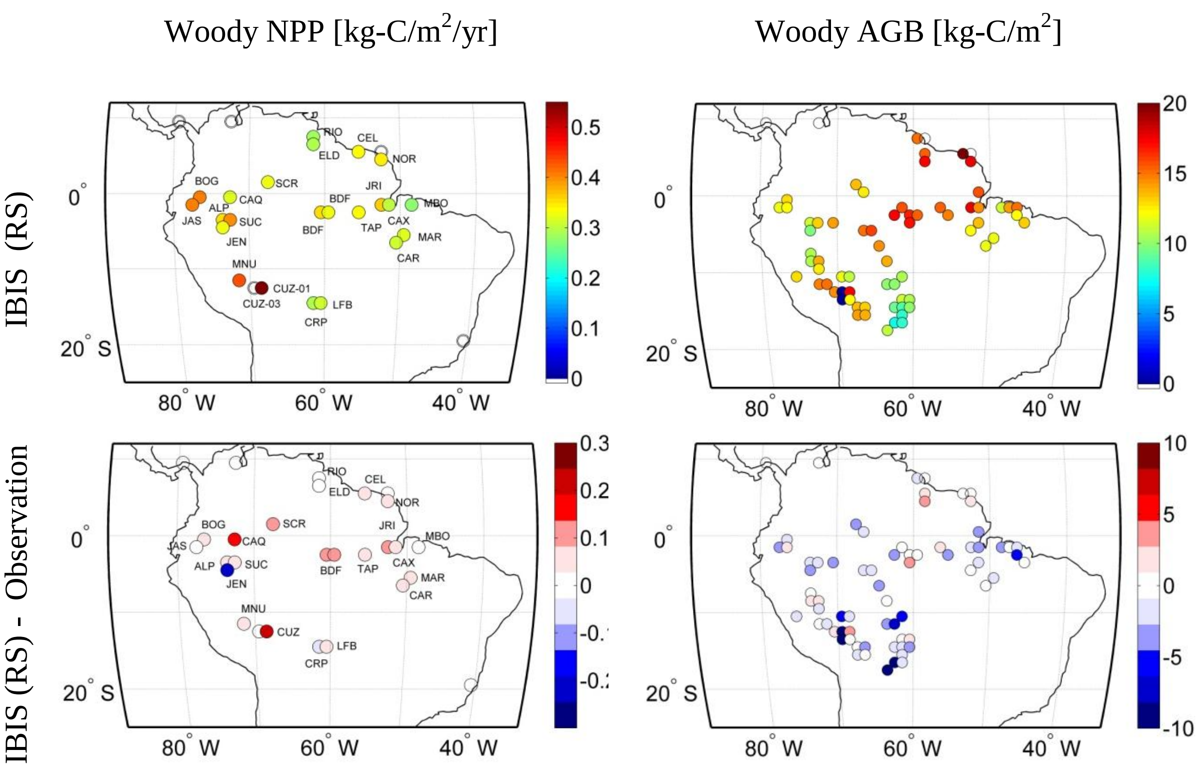


Figure D1: The woody above ground net primary productivity (left column) and the woody above ground live biomass (right column). First row shows the IBIS regional simulation (RS) for sites where there was NPP_w [kg-C/m^2/yr] (Series A+B) and AGB_w [Kg-C/m^2]

(Series C+D) field data. In the second row are the difference between IBIS simulated data (RS) and observation for the respective field sites.

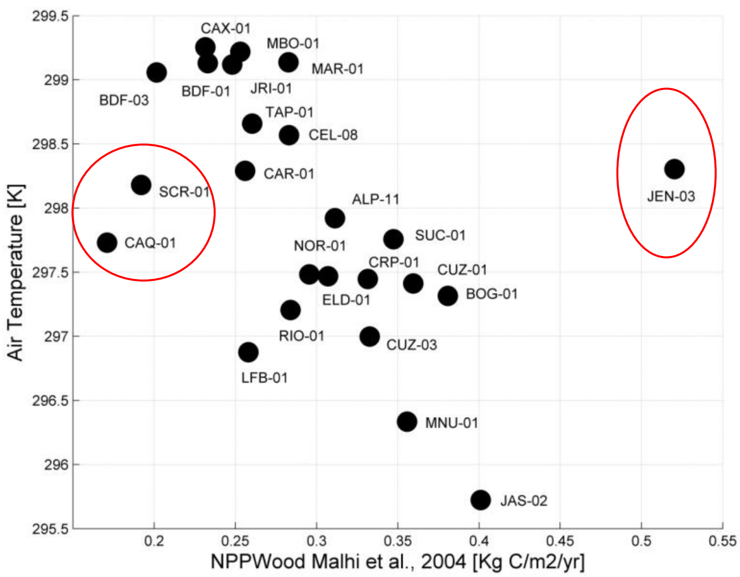


Figure D2: Relationship between observed NPP_w from Malhi et al., 2004 and annual mean air temperature. The red circles show the identified outliers, in relation to the observed NPP_w and Air Temperature relationship.

The above ground biomass analyses of differences between simulations and ground based observations are higher for the sites CHN (La Chonta, Bolivia) and AMB (Amboro Rio Saguayo, Bolivia) located at south of the basin where the dry season is long. There were no clear conclusion on why these locations have very high values in the observations, and very low values in the simulated AGB. It is clear however the importance of accurate information on the woody residence time in the overall agreement of the AGB_w simulated and the field data.

References

Domingues, T. F., Berry, J. A., Martinelli, L. A., Ometto, J. P. H. B. and Ehleringer, J. R.: Parameterization of Canopy Structure and Leaf-Level Gas Exchange for an Eastern Amazonian Tropical Rain Forest (Tapajós National Forest, Pará, Brazil), Earth Interactions, 9, 17, 1-23, 10.1175/ei149.1, 2005.

Fyllas, N. M., Patiño, S., Baker, T. R., Bielefeld Nardoto, G., Martinelli, L. A., Quesada, C. A., Paiva, R., Schwarz, M., Horna, V., Mercado, L. M., Santos, A., Arroyo, L., Jiménez, E. M., Luizão, F. J., Neill, D. A., Silva, N., Prieto, A., Rudas, A., Silviera, M., Vieira, I. C. G., Lopez-Gonzalez, G., Malhi, Y., Phillips, O. L. and Lloyd, J.: Basin-wide variations in foliar properties of Amazonian forest: phylogeny, soils and climate, Biogeosciences, 6, 11, 2677-2708, 10.5194/bg-6-2677-2009, 2009.

Körner, C.: Responses of Humid Tropical Trees to Rising CO2, Annual Review of Ecology, Evolution, and Systematics, 40, 1, 61-79, doi:10.1146/annurev.ecolsys.110308.120217, 2009.

Malhi, Y., Baker, T. R., Phillips, O. L., Almeida, S., Alvarez, E., Arroyo, L., Chave, J., Czimczik, C. I., Fiore, A. D., Higuchi, N., Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Montoya, L. M. M., Monteagudo, A., Neill, D. A., Vargas, P. N., Patiño, S., Pitman, N. C. A., Quesada, C. A., Salomão, R., Silva, J. N. M., Lezama, A. T., Martínez, R. V., Terborgh, J., Vinceti, B. and Lloyd, J.: The above-ground coarse wood productivity of 104 Neotropical forest plots, Global Change Biology, 10, 5, 563-591, 10.1111/j.1529-8817.2003.00778.x, 2004.

Malhi, Y., Wood, D., Baker, T. R., Wright, J., Phillips, O. L., Cochrane, T., Meir, P., Chave, J., Almeida, S., Arroyo, L., Higuchi, N., Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Monteagudo, A., Neill, D. A., Vargas, P. N., Pitman, N. C. A., Quesada, C. A., Salomão, R., Silva, J. N. M., Lezama, A. T., Terborgh, J., Martínez, R. V. and Vinceti, B.: The regional variation of aboveground live biomass in old-growth Amazonian forests, Global Change Biology, 12, 7, 1107-1138, 10.1111/j.1365-2486.2006.01120.x, 2006.

Malhi, Y., Doughty, C. and Galbraith, D.: The allocation of ecosystem net primary productivity in tropical forests, Philosophical Transactions of the Royal Society B: Biological Sciences, 366, 1582, 3225-3245, 10.1098/rstb.2011.0062, 2011.

Mercado, L. M., Lloyd, J., Dolman, A. J., Sitch, S. and Patiño, S.: Modelling basin-wide variations in Amazon forest productivity – Part 1: Model calibration, evaluation and upscaling functions for canopy photosynthesis, Biogeosciences, 6, 7, 1247-1272, 10.5194/bg-6-1247-2009, 2009.

Mercado, L. M., Patiño, S., Domingues, T. F., Fyllas, N. M., Weedon, G. P., Sitch, S., Quesada, C. A., Phillips, O. L., Aragão, L. E. O. C., Malhi, Y., Dolman, A. J., Restrepo-Coupe, N., Saleska, S. R., Baker, T. R., Almeida, S., Higuchi, N. and Lloyd, J.: Variations in Amazon forest productivity correlated with foliar nutrients and modelled rates of photosynthetic carbon supply, Philosophical Transactions of the Royal Society B: Biological Sciences, 366, 1582, 3316-3329, 10.1098/rstb.2011.0045, 2011.

Phillips, O. L., Baker, T. R., Arroyo, L., Higuchi, N., Killeen, T. J., Laurance, W. F., Lewis, S. L., Lloyd, J., Malhi, Y., Monteagudo, A., Neill, D. A., Núñez Vargas, P., Silva, J. N. M., Terborgh, J., Vásquez Martínez, R., Alexiades, M., Almeida, S., Brown, S., Chave, J., Comiskey, J. A., Czimczik, C. I., Di Fiore, A., Erwin, T., Kuebler, C., Laurance, S. G., Nascimento, H. E. M., Olivier, J., Palacios, W., Patiño, S., Pitman, N. C. A., Quesada, C. A., Saldias, M., Torres Lezama, A. and Vinceti, B.: Pattern and process in Amazon tree turnover, 1976–2001, Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 359, 1443, 381-407, 10.1098/rstb.2003.1438, 2004.

Quesada, C. A., Lloyd, J., Schwarz, M., Patiño, S., Baker, T. R., Czimczik, C., Fyllas, N. M., Martinelli, L., Nardoto, G. B., Schmerler, J., Santos, A. J. B., Hodnett, M. G., Herrera, R., Luizão, F. J., Arneth, A., Lloyd, G., Dezzeo, N., Hilke, I., Kuhlmann, I., Raessler, M., Brand, W. A., Geilmann, H., Moraes Filho, J. O., Carvalho, F. P., Araujo Filho, R. N., Chaves, J. E., Cruz Junior, O. F., Pimentel, T. P. and Paiva, R.: Variations in chemical and physical properties of Amazon forest soils in relation to their genesis, Biogeosciences, 7, 5, 1515-1541, 10.5194/bg-7-1515-2010, 2010.