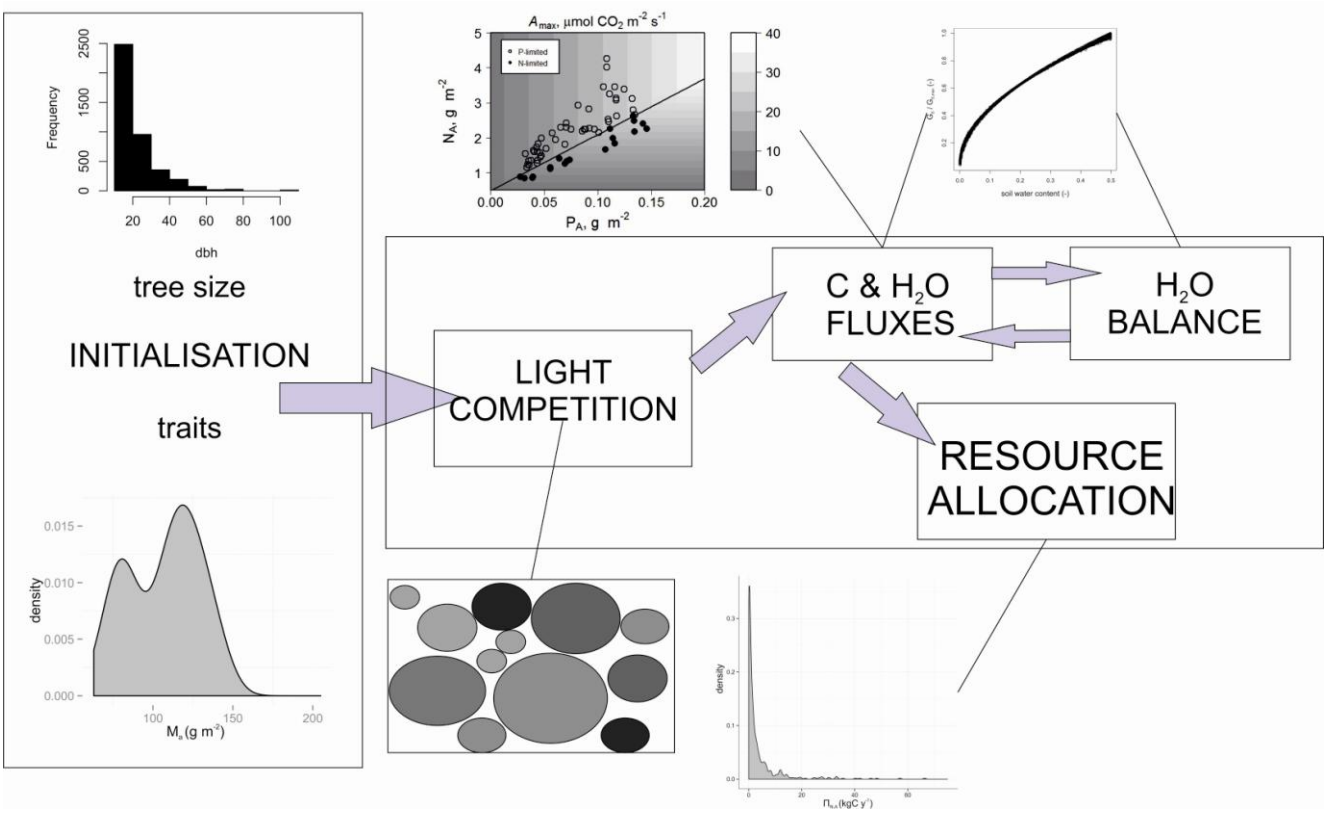
Supplement S1: The Trait-based Forest Simulator (TFS) description

Overview

Trait-based Forest Simulator (TFS) is an individual-based forest model, i.e. it simulates key ecophysiological processes for each tree in a stand. In this version of the model, stand structure is prescribed in terms of the number of trees and distribution of their diameter at breast height (*d*), although the model is not spatially explicit. The aim of the model is to simulate carbon and water fluxes at small scale forest stands. Here it is parameterised for Amazonian tropical trees although it can be easily adapted to different biomes, given the appropriate data. The model runs on an hourly time-step and it simulates photosynthetic carbon assimilation, growth and maintenance respiration and carbon allocation for each tree in a given stand. Competition for light is approximated through the perfect plasticity model of Purves et al. (2007), assuming flat top canopy trees, i.e. that all of their foliage is found as a disc at the top of their stem. This simple tree architecture approximates light competition, by identifying canopy and sub-canopy trees. Four key functional traits: leaf mass per area [M_a (g m^{-2})], leaf dry mass N and leaf P concentrations [N_{Lm} and P_{Lm} respectively (mg g^{-1})] as well as wood density [D_W (g cm^{-3})] are also predefined for each stand, based on data presented in Baker et al. (2009) and Fyllas et al. (2009). A Monte-Carlo method is used to initialise tree properties, based on the observed stand level trait distribution by assigning randomly trait values for the four functional characteristics following the observed distributions. The basic components of the model are presented in Fig. A1.

Figure S1.1: The basic components of the model and information flow among them. Tree by tree traits and size initialisation is taking place at the beginning of each simulation. Carbon fluxes are estimated hourly while water fluxes, gross and net primary productivity are estimated on a daily basis.

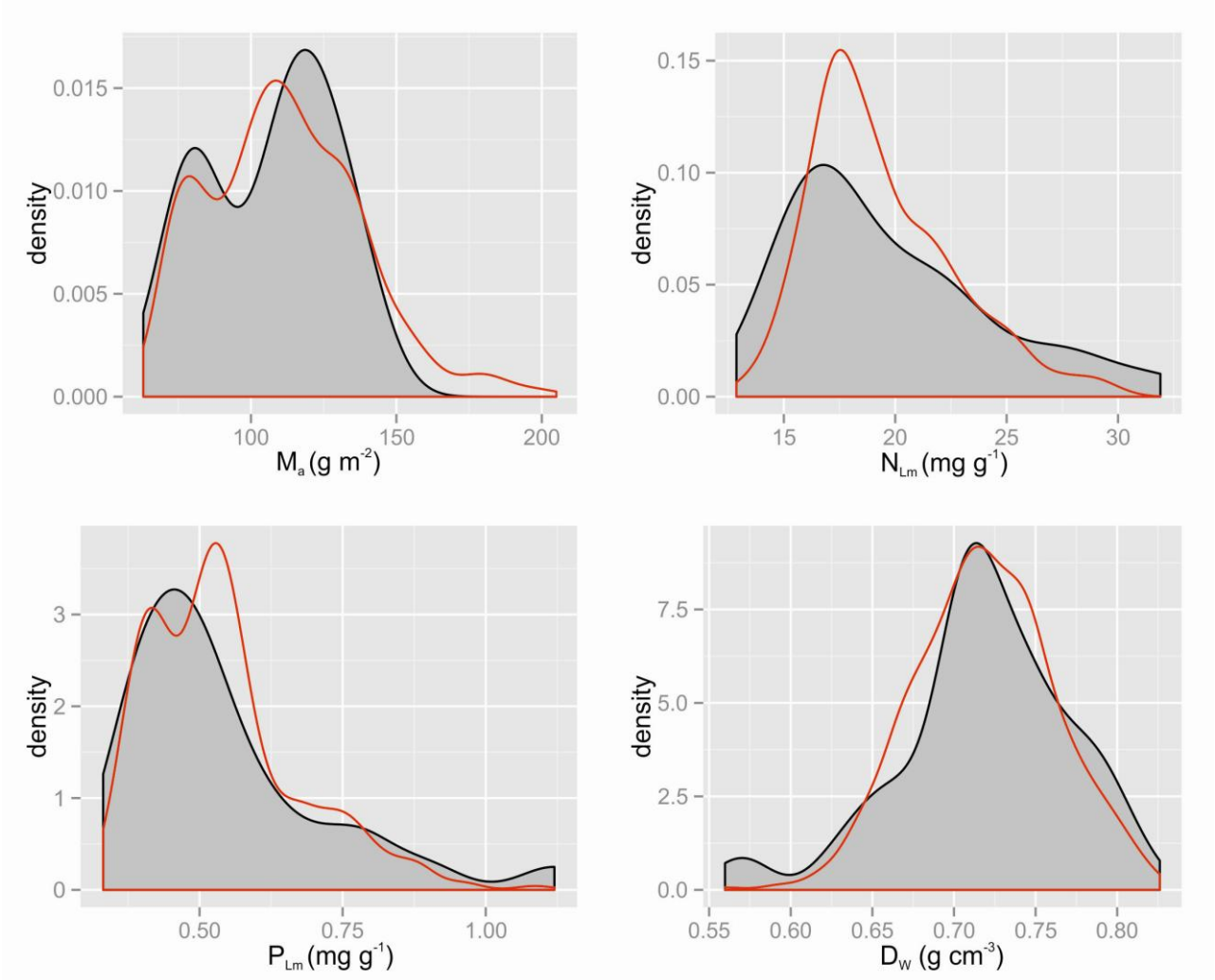


Size and functional traits distributions (Initialisation component)

There is no species or plant functional group description of trees in a TFS stand. The four key functional characters (M_a, N_{Lm}, P_{Lm} and D_W) are used to "define" individuals and capture the importance of functional diversity within a stand. These characters have a direct effect on the architecture and the photosynthetic capacity of a tree. Tree size distribution is prescribed based on the RAINFOR (Malhi et al., 2002) inventory dataset, using d and the four functional traits as the key parameters to estimate other tree components of interest, such as above and below ground biomass, photosynthetic capacity etc.

For the forest stands of interest a set of foliage and structural traits has been recorded and analysed as shown in Patiño et al. (2012) and Fyllas et al. (2009). Thus a sample distribution of M_a, N_{Lm}, P_{Lm} and D_W, is known for each study site. In order to assign the four key traits to each one of trees recorded in the inventory data, a data-driven random vector generation algorithm has been employed (Taylor & Thompson, 1986). The purpose of this algorithm is to generate random trait suites based on the multivariate trait sample of each site by maintaining the underlying distribution. An example of the recorded and generated distributions can be found in Fig. A2.

Figure S1.2: Generation of pseudo-observations of functional traits suites in BNT-04, using the Taylor & Thompson (1986) algorithm embedded in TFS. The observation sample consisted of 28 trait suites, with 620 pseudo-observations generated. Observed distribution of M_a, N_{Lm}, P_{Lm}, and D_W displayed in grey colour, with red colour for the generated ones.



Definition, Allometry and Stoichiometry of Individual Trees in TFS

Each tree is defined as a stem with a flat circular canopy at its top. The four key functional characters (M_a, N_{Lm}, P_{Lm} and D_W) are used to separate between individuals. These characters have a direct effect on a tree's architecture and growth through the regulation of the amount of foliage a tree can support as well as the photosynthetic capacity of leaves.

Tree height [H(m)], Crown Area [C_A (m^2)] and Crown Depth [C_D (m)] are calculated using the allometric equations in Poorter et al. (2006) and are not related with any of the functional traits:

$$H = 61.7 \cdot (1 - \exp(-0.0352 \cdot d^{0.694}) \quad \text{(A1)}$$

$$C_A = \exp\ -1.853 + 1.888 \cdot \log(H) \quad \text{(A2)}$$

$$C_D = \exp\ -1.169 + 1.098 \cdot \log(H) \quad \text{(A3)}$$

Total aboveground biomass B_{ABG} (kg) is calculated using equation from Chave (2005), which takes into account the diameter, the height and the D_W of a tree:

$$B_{ABG} = 0.0509 \cdot d^2 \cdot D_W \cdot H \quad \text{(A4)}$$

Total root (B_R) and stem (B_S) biomass are estimated from the equations of Niklas (2005) and Enquist & Niklas (2002) respectively:

$$B_R = 0.034 \cdot (B_{ABG})^{0.941} \quad \text{(A5)}$$

$$B_S = 2.610 \cdot (B_R)^{1.100} \quad \text{(A6)}$$

Foliage area (L_A m^2) is given from

$$L_A = L_D \cdot C_V \quad \text{(A7)},$$

with C_V the crown volume (m^3), estimated as

$$C_V = C_A C_D \quad \text{(A8)}$$

and assuming that leaf area density (L_D) decreases with height (Meir et al., 2000) based on the equation:

$$L_D = 0.5 - 0.3\frac{H}{H_{max}} \quad \text{(A9)}, \text{ where } H_{max} \text{ the height of the tallest tree in the canopy.}$$

The foliage biomass (B_L (kg)) is then:

$$B_L = 0.001 \cdot M_a L_A \quad \text{(A10)}$$

With fine root biomass (B_{FR}) assumed to be equal to leaf biomass and thus:

$$B_{FR} = B_L \text{ and } B_{CR} = B_R - B_{FR} \quad \text{(A11)}$$ the coarse root biomass (B_{CR}).

Thus trees with a higher D_W have a higher stem and root biomass, while trees with higher M_a support a higher leaf biomass and thus have a relative higher maintenance cost (through respiration).

The tree level leaf area index (L) is a central variable in terms of estimating the absorbed radiation and scaling the photosynthetic capacity of each tree. Tree specific leaf area index (L) is estimated as:

$$L = \frac{L_A}{C_A} \quad \text{(A12)}$$

The nitrogen content of each biomass component is estimated using the scaling relationships of Kerkhoff et al. (2006), when N_L is known. Thus the N concentration in stems (N_S) and roots (N_R) are given from a scaling relationship of the form:

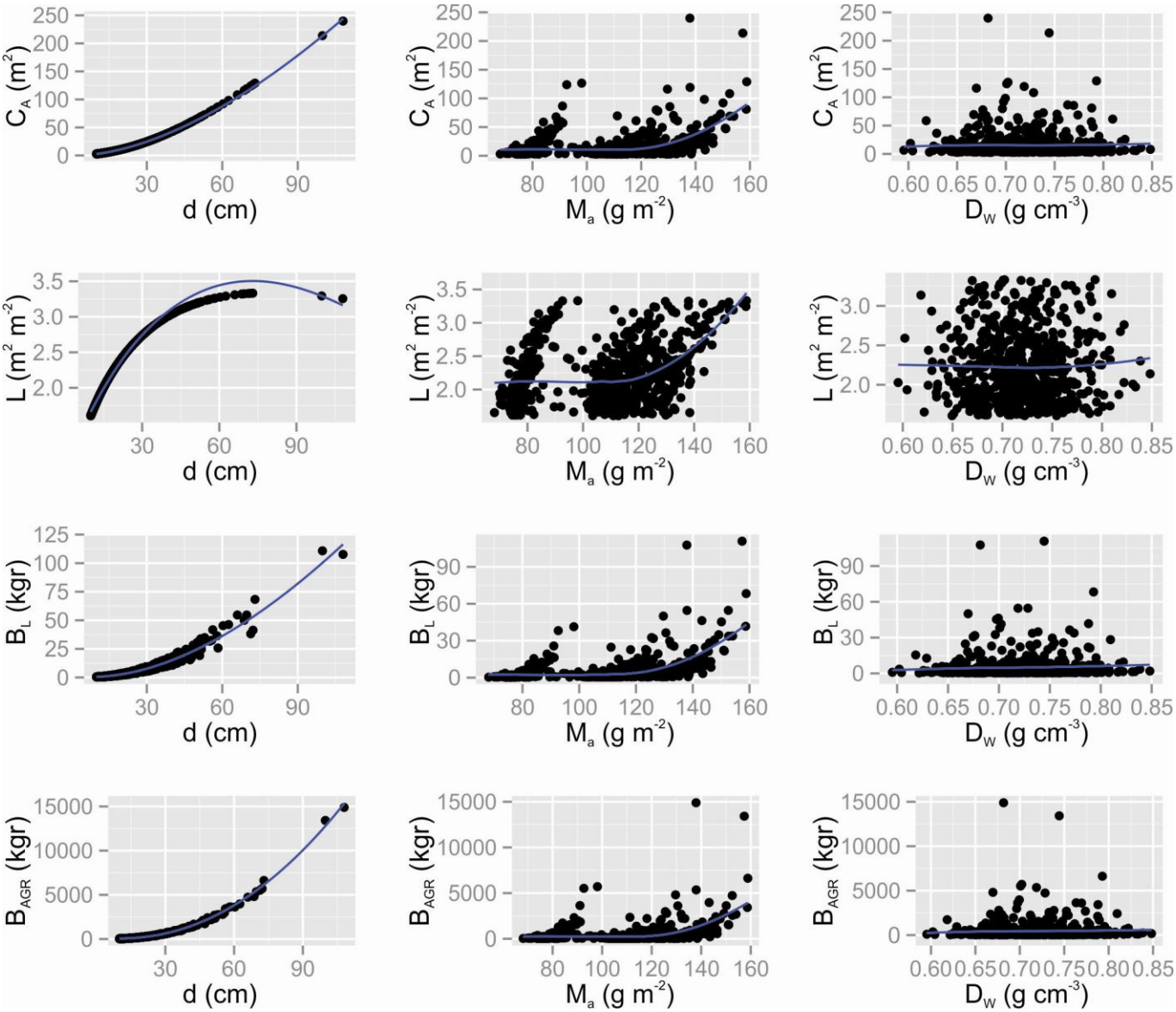
$$N_S = a_S \cdot (N_{Lm})^{b_S} \quad \text{(A13a)}$$

$$N_R = a_R \cdot (N_{Lm})^{b_R} \quad \text{(A13b)}$$

with a_S, b_S, a_R and b_R empirical coefficients given in Kerkhoff et al. (2006).

The way the basic tree architecture changes with the size of the tree and relates to key functional characters is summarised in Fig. A3.

Figure S1.3: Tree-level C_A, L, B_L and B_{AGR} for each tree in plot BNT-04 against diameter at breast height (d), leaf dry mass per area (M_a) and wood density (D_W)



The leaf-level photosynthetic rates are driven by V_{max} and J_{max} (μmol m^{-2} s^{-1}) which are potentially limited by either the leaf N (N_L) or P (P_L) concentrations (mass basis) , according to the formula:

$$V_{\max} = \min\ a_{\mathrm{NV}} + v_{\mathrm{NV}} N_{\mathrm{L}}, a_{\mathrm{PV}} + v_{\mathrm{PV}} P_{\mathrm{L}}\ \times M_{\mathrm{a}} \quad \text{(A14)}$$

$$J_{\max} = \min\ a_{\mathrm{NJ}} + v_{\mathrm{NJ}} N_{\mathrm{L}}, a_{\mathrm{PJ}} + v_{\mathrm{PJ}} P_{\mathrm{L}}\ \times M_{\mathrm{a}} \quad \text{(A15)}$$

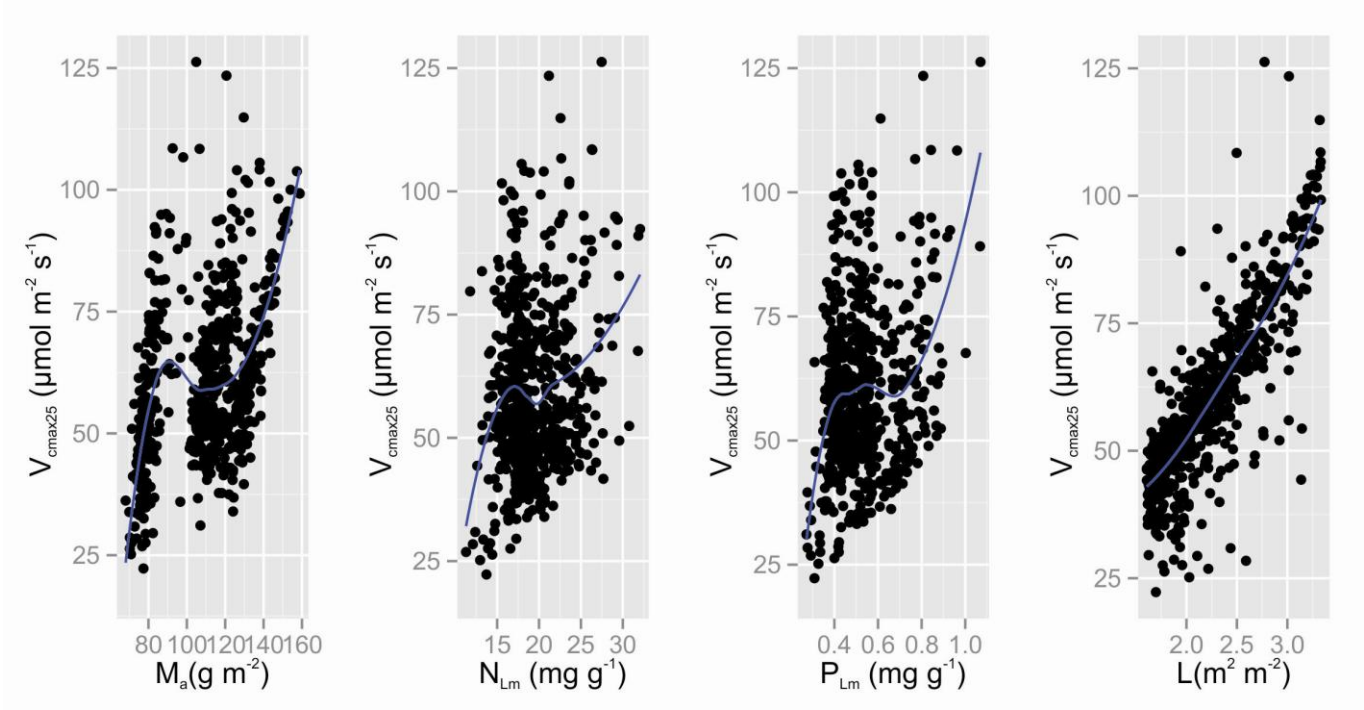
with a_{NV}, a_{NJ}, a_{PV}, a_{PJ} in (μmol g^{-1} s^{-1}) and v_{NV}, v_{NJ}, v_{PV}, v_{PJ} in (mmol g^{-1} s^{-1}) empirical coefficients (Domingues et al., 2010).

The canopy level photosynthetic capacity (V_{Cmax}) is then estimated by integrating the leaf level V_{max} for the leaf area index of each tree, i.e.:

$$V_{C\max} = \frac{L \cdot V_{\max} \cdot [1 - \exp(-k_{\mathrm{v}})]}{k_{\mathrm{v}}} \quad \text{(A16)}$$

where $k_v = k_N \cdot L$ and k_N= exp (0.00963 V_{max} -2.43) (17), as suggested in Lloyd et al. (2010). Changes of V_{Cmax} with N_{Lm}, P_{Lm}, M_a and L are summarised in Fig. A4.

Figure S1.4: Canopy level V_{Cmax} for each tree in BNT-04 as a function of N_{Lm}, P_{Lm}, M_a and L



Canopy Architecture and Radiation Environment

The flat-top version of the perfect plasticity model of Purves et al. (2007) has been used in the current version of TFS to characterise canopy and sub-canopy trees (in or out of the canopy). The flat-top version assumes that all of a tree's foliage is found at the top of its stem. A canopy height Z^* is estimated for a forest stand defining canopy and sub-canopy trees. By summing up the crown area (C_A) of all trees in the stand, Z^* is defined as the height of the last tree that enters to the sum before the cumulative crown area is equal to the plot area.

Canopy trees are absorbing a mean daily amount of shortwave solar radiation equal to the sum of mean beam, diffuse and scattered daily radiation (all in Wm^{-2}), i.e. $S_{can} = S_{beam} + S_{diffuse} + S_{scattered}$ while sub-canopy tree only receive $S_{sub} = S_{diffuse} + S_{scattered}$, in correspondence to the sun-shade model of de Pury and Farquhar (1997). Thus based on Wang & Leuning (1998):

$$S_{\text{can}} = Q_{\text{d}}(1-\rho_{\text{d}})\,\text{k}_{\text{d}}^{*}\,\Psi\left\langle k_{\text{d}}^{*}+k_{\text{b}}\right\rangle + Q_{\text{b}}(1-\rho_{\text{b}})k_{\text{b}}^{*}\Psi\left\langle k_{\text{b}}^{*}+k_{\text{b}}\right\rangle + Q_{\text{b}}(1-\omega)k_{\text{b}}\left[\Psi\left\langle k_{\text{b}}\right\rangle - \Psi\left\langle 2k_{\text{b}}\right\rangle\right] \quad (18a)$$

$$S_{\text{sub}} = Q_{d}(1-\rho_{\text{d}})k_{\text{d}}^{*}\left[\Psi\left\langle k_{\text{d}}^{*}\right\rangle - \Psi\left\langle k_{\text{d}}^{*}+k_{\text{b}}\right\rangle\right] + Q_{\text{b}}(1-\rho_{\text{b}})k_{\text{b}}^{*}\left[\Psi\left\langle k_{\text{b}}^{*}\right\rangle - \Psi\left\langle k_{\text{b}}^{*}+k_{\text{b}}\right\rangle\right] - Q_{b}(1-\omega)k_{\text{b}}\left[\Psi\left\langle k_{\text{b}}\right\rangle - \Psi\left\langle 2k_{\text{b}}\right\rangle\right] \quad (18b)$$

$$\text{with}\,\Psi\left\langle x\right\rangle = \frac{1-\exp(-x\cdot L)}{x} \quad (18c)$$

where Q_{b} and Q_{d} are hourly mean shortwave direct and diffuse radiation (both in Wm^{-2}); ρ_{b}, ρ_{d} and ω are leaf direct beam reflectance, leaf diffuse reflectance and leaf scattering coefficient, all unitless; $k_{\text{b}}, k_{\text{b}}^{*}, k_{\text{d}}, k_{\text{d}}^{*}$ are black leaves beam, black leaves diffuse, canopy beam and canopy diffuse extinction coefficients. Estimation of the direct and diffuse fraction of solar radiation is achieved by implementing the Spitters et al. (1986) approximation.

The longwave radiation absorbed by canopy trees and sub-canopy trees (both in Wm^{-2})is given by:

$$L_{\text{can}} = -k_{\text{d}}\sigma T_{\text{a}}^{2}\;\;\varepsilon_{\text{l}}\;\;1-\varepsilon_{\text{a}}\;\;\Psi\left\langle k_{\text{b}}+k_{\text{d}}\right\rangle + (1-\varepsilon_{\text{s}})(\varepsilon_{\text{l}}-\varepsilon_{\text{a}})\Psi\left\langle 2k_{\text{d}}\right\rangle\Psi\left\langle k_{\text{b}}-k_{\text{d}}\right\rangle \quad (19a)$$

and

$$L_{\text{sub}} = -k_{\text{d}}\sigma T_{\text{a}}^{2}\;\;\varepsilon_{\text{l}}\;\;1-\varepsilon_{\text{a}}\;\;\Psi\left\langle k_{\text{b}}\right\rangle -\;\;1-\varepsilon_{\text{s}}\;\;\;\varepsilon_{\text{l}}-\varepsilon_{\text{a}}\;\;\exp(-\text{k}_{\text{d}}\cdot\text{L})\Psi\left\langle k_{\text{d}}\right\rangle\;\;-L_{\text{can}} \quad (20)$$

respectively. This is as suggested in Wang & Leuning (1998). Here ε_{l} ,ε_{a} and ε_{s} are the leaf, sky and soil emissivity, with ε_{a} being estimated by the formula of Brutsaert (1975).

Photosynthesis

The Farquhar et al. (1980) model of leaf photosynthesis is used to estimate mean hourly rates of carbon assimilation at the leaf level. As discussed above the maximum photosynthetic rate is regulated by N_{L} or P_{L} through the co-limitation model of Domingues et al. (2010). The Rubisco limited net assimilation rate (μmol $\text{m}^{-2}\,\text{s}^{-1}$)is given by the equation:

$$A_{\text{V}}^{*} = V_{C\max}\left(\frac{C_{\text{c}}-\Gamma^{*}}{K_{\text{C}}(1+\frac{p_{O_2}}{K_{\text{O}}})+C_{\text{c}}}\right) \quad \text{(A21)}$$

where C_{c} is the CO_2 concentration in the chloroplast (μmol mol^{-1}), Γ* the CO_2 compensation point, p_{O2} the intercellular partial pressure of O_2, K_{C} and K_{O} are the Michaelis-Menton constants for carboxylation and oxygenation by Rubisco. A_{V}* is the assimilation rate in the absence of leaf respiration in the light, which is estimated later on. The light limited assimilation rate (μmol $\text{m}^{-2}\,\text{s}^{-1}$) is estimated according to:

$$A_{\text{j}} = \frac{J}{4}\left(\frac{C_{\text{c}}-\Gamma^{*}}{C_{\text{c}}+2\Gamma^{*}}\right) \quad \text{(A22)}$$

with J the potential rate of electron transport modelled as a non-rectangular hyperbolic function of the absorbed quantum flux (I_2in μmol quanta $\text{m}^{-2}\text{s}^{-1}$), the absorbed irradiance reaching photosystem II ($J_{\max}$ in μmol $\text{m}^{-2}\text{s}^{-1}$) and the curvature factor θ:

$$\theta J^{2} - (I_{2}+J_{\max})J + I_{2}J_{\max} = 0 \quad \text{(A23)}$$

I_2 is estimated from estimates of the amount incoming photosynthetic active radiation (I_0) reaching the foliage of each tree, canopy reflectance (r),transmittance (t) and quantum yield (a) according to

$$I_2 = \alpha_{I2} S \quad \text{(A24)}$$

with α_{I2}=0.30 the light use efficiency. Shortwave radiation (either S_{can} or S_{sub}) (Wm^{-2}) is transformed to *PAR* (μmol $m^{-2}s^{-1}$) by multiplying with a factor of 2.025. The mean hourly net CO_2 assimilation rate (A) is then estimated as the minimum between A_V and A_J. Temperature sensitivities for V_{max}, J_{max}, Γ^* and the CO_2 and O_2 Michaelis constants K_C and K_O respectively, are estimated according to Bernacchi et al. (2001) and Lloyd et al. (1995). Finally, the total daily photosynthetic carbon assimilation for each tree (A_d) is calculated as the sum of hourly A multiplied by the crown area of the tree.

Stomatal Conductance

Maximum (no water stress) stomatal conductance ($g_{,max}$) is estimated following the Medlyn et al. (2011,2012) equation:

$$g_{s,max} = g_0 + 1.6\left(1 + \frac{g_1}{\sqrt{D_C}}\right)\frac{A_n}{C_a} \quad \text{(A25)}$$

with g_0 (mol m^{-2} s^{-1}) the minimum stomatal conductance, g_1(-) an empirical coefficient that represents the water use efficiency of the plant, and DC the leaf-to-atmosphere vapour pressure difference. Values of g_0 and g_1 that lead to the best model performance were different between sites, as indicated by the model calibration procedure. For the basin wide simulations constant values of g_0=0.020 (mol m-2 s-1) and g_1=5.0 (-) were used, close to the estimates of Domingues et al. (2013). In future versions of the model, g_0 and g_1 should be related with other functional traits. The optimum stomatal conductance is subsequently reduced to the actual g_s by multiplying the second term of equation A25 with the water stress coefficient described in the "Water Balance and Soil Water Stress" section.

Respiration

Tree respiration includes a growth and a maintenance component, computed daily. Growth respiration is considered as a constant fraction of daily photosynthesis equal to 0.25 (Cannell & Thornley, 2000). In TFS three alternative formulation to calculate maintenance respiration are implemented.

Mori Method

The first method to estimate the maintenance respiration of a tree is based on the Mori et al. (2010) empirical model. In this model a mixed-power scaling equation is being used which only takes into account the size of a tree to estimate the total maintenance respiration R_m (μmol CO_2 s^{-1}):

$$R_m = -\log\left[\frac{1}{GB_{tot}^{g}} + \frac{1}{HB_{tot}^{h}}\right] \quad \text{(A26)}$$

with $B_{tot}=B_{ABG}+B_R$ the total tree biomass and *g, h, G* and *H* empirical coefficients provided in Mori et al. (2010*) viz* *g*= 1.408, *h*=0.805, *G*=201.87 and *H*=0.410.

Modified Reich Method

The second method is based on findings of a strong coupling between respiration rates and nitrogen content of different plant components (Reich et al., 2008). Maintenance respiration rates of leaves, stems and roots are calculated based on their mass and nitrogen content. The nitrogen content of each component is estimated using the scaling relationships of Kerkhoff et al. (2006), when N_L is known (equations A13a and A13b).

Stem (R_{mS}) and coarce root (R_{mCR}) respiration rates are expressed as a function of their nitrogen content. Leaf maintenance respiration R_{mL} is not estimated as in Reich et al. (2008), but it is rather coupled to photosynthesis assuming it represents a constant fraction of V_{max} (Scheiter & Higgins, 2009), in order to account for potential N and/or P limitations. Fine root respiration R_{mFR} is assumed to be equal to R_{mL}. After transforming N_S and N_R in (mmol g^{-1}) the maintenance respiration of each component is given as:

$R_{mL} = 0.015 V_{Cmax}$ (A27) in μmol $CO_2 s^{-1}$

$R_{mS} = g(T)\alpha_{SS} B_S \tau_S N_S^{\sigma_S}$ (A28) in nmol CO_2 s^{-1}

$R_{mCR} = g(T)\alpha_{RS} B_{CR} \tau_R N_R^{\sigma_R}$ (A29) in nmol CO_2 s^{-1}

with τ_i and σ_i empirical coefficients reported in Reich et al. 2008 and $g(T)$ the temperature dependence function of Tjoelker et al. (2001). Here α_{SS} and α_{RS} are the sapwood fractions of stem and coarse root biomass (both considered constant with size) and equal to 0.025 (Scheiter & Higgins, 2009). Thus the overall maintenance respiration (R_m in kg C) is given from equation:

$R_m = R_{mL} + R_{mS} + R_{mFR} + R_{mCR}$ (A30)

Sapwood Volume Method

The third method is a combined approach which replaces the use of a constant sapwood fraction for stems. Total maintenance respiration is again divided to leaf, stem and root respiration (equation 30). Foliage respiration is again estimated as a fraction of V_{max} (equation A27) and fine root respiration is assumed to be equal to foliage respiration. Stem maintenance respiration is calculated as:

$R_{mS} = g(T)\delta S_V$ (A31)

with S_V the sapwood volume and δ (39.6 μmol CO_2 s^{-1} m^{-3}) a respiration rate per sapwood volume measured for tropical trees (Ryan et al., 1994). Sapwood volume is estimated by inversing the pipe model and assuming that the ratio of leaf area to sapwood area (Φ_{LS}) increases with the height and the wood density for tropical trees following (Calvo-Alvarado et al., 2008; Meinzer et al., 2008):

$\Phi_{LS} = 0.5 \times (\lambda_1 + \lambda_2 \cdot H + \delta_1 + \delta_2 D_W)$ (A32),

with λ_1=0.066 m^2 cm^{-2}, λ_2=0.017 m cm^{-2}, δ_1= - 0.18 m^2 cm^{-2} and δ_2=1.6 cm^3 g^{-1}. Sapwood area (m^2) and volume (m^3) are then calculated from:

$S_A = L_A / \Phi_{LS}$ (A33) and

$S_V = S_A \cdot (H - C_D)$ (A34)

Coarse root maintenance respiration is estimated as in (Scheiter& Higgins, 2009):

$R_{mCR} = 0.218 \cdot \frac{\alpha_{RS} \cdot B_{CR}}{\Phi_{CN}} \cdot g(T)$ (A35) where Φ_{CN} is the root C:N ratio estimated on the basis of the simulated N_R assuming a dry weight carbon fraction of 0.5.

Water Balance and Soil Water Stress

A single-layer soil bucket model is used in the current version of the model to estimate soil water content and the down-regulation of stomatal opening in case of limited soil water. We are aware that this is a component that needs further improvement in the future but for the purpose of this study which is to explore to first order the basic functioning of forest stand carbon uptake and water loss a single-layer soil model should be sufficient. In contrast to most ecosystem fluxes model, where photosynthetic rates are directly regulated by water availability (Cox et al. 1998; Clark et al. 2011), we couple water 'stress' to reduction of canopy conductance by estimating a daily fractional available soil water content ϑ_i, for each *i* tree in the stand given from:

$$\vartheta_i = \left[\frac{W_i - W_w}{W_{FC} - W_w} \right] \quad \text{(A36)},$$

where W_i the available water for tree i, W_{FC} is the soil water content at field capacity (matric potential of 0.033 MPa) and W_W is the soil water content at wilting (matric potential of 1.5MPa), both estimated using the van Genuchten (1980) model with the soil-type specific parameters reported in Hodnett & Tomasella (2002).

The estimation of W_i at time *t* is summarized in the following graphic and calculated as:

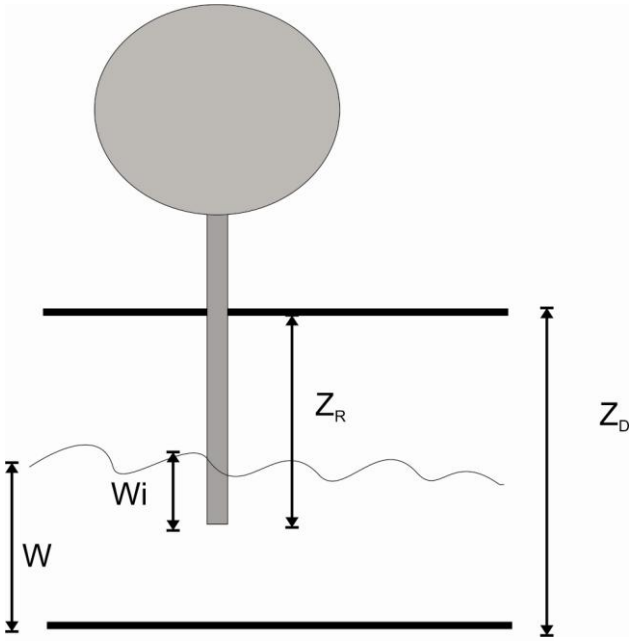
$$W_{i,t} = W_{t-1} + (P_t - E_{tot,t} - Q_t) + Z_{R,i} - Z_D \quad \text{(A37)}$$

Here W_{t-1} is the previous day's (stand level) soil water column, P_t is the daily total precipitation, $E_{tot,t}$ the daily total (stand level) evaporation, Q_t the run-off, $Z_{R,i}$ is the root depth of tree i, and Z_D the soil depth all expressed in mm. The rooting depth of each tree is estimated in a similar way to Scheiter and Higgins (2009), as the biomass needed to construct a root cylinder of radius R_r (R_r= 0.15m) with a density D_r (D_r=100 kg m-3):

$$Z_R = \frac{B_{FR}}{\pi D_r R_r^2} \quad \text{(A38)}$$

A tree specific water stress term γ_i that has a direct effect on stomatal conductance (as a multiplier) is subsequently estimated from, $\gamma_i = \vartheta_i^n$ (A 39)

As discussed in Keenan et al. (2010) the exponent in the last equation, is a measure of the non-linearity of the effects of soil water stress on stomatal conductance. The smaller the value of n, the less sensitive is the overall canopy conductance to soil water stress. In our case we found a value of *n*=0.5 to give best agreement with observations in regards to the response of stomatal conductance to changes in water availability and the long-term simulation of carbon fluxes. The way stomatal conductance (given here as the ratio of $g_S/g_{S,max}$) varies with θ_i is graphically illustrated in the following figure.



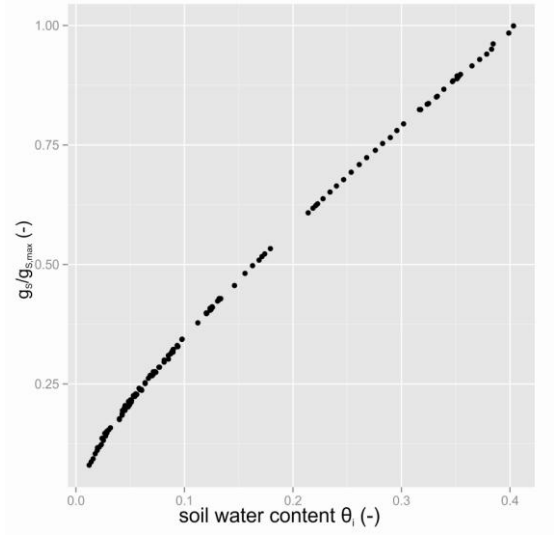


Figure S1.5: Variation of the $g_S/g_{S,max}$ with soil water content at Caxiuana.

Canopy Transpiration

An iterative procedure (Medlyn et al., 2007) is used to solve the energy balance for the canopy of each tree. The algorithm initially assumes a canopy-to-air vapour pressure deficit D_C equal to the estimated vapour pressure deficit (*i.e.* with leaf temperature (T_L) equal to air temperature) and a chloroplast CO_2 concentration (C_c) of $0.7C_a$. It then calculates leaf photosynthetic rate (A_n) and stomatal conductance (g_s), as well as boundary layer and radiation conductance. Subsequently the Penman-Montheith equation is used to estimate canopy transpiration and then new T_L,D_C and C_C. Convergence is achieved if T_L difference between steps is less than 0.1 degrees ^oC.

Following Medlyn et al. (2007), the total leaf conductance to heat (g_H) is equal to:

$$g_H = 2\times(g_{bHf} + g_{bHu} + g_r) \quad \text{(A40)}$$

with g_{bHf} the boundary layer conductance for free convection (mol m^{-2} s^{-1}):

$$g_{bHf} = \frac{0.5D_H(1.6\cdot10^8\,|T_L - T_a\,|\,w^3)^{0.25}}{w}\left(\frac{rP}{RT_K}\right) \quad \text{(A41)}$$

D_H= 21.5x10^{-6} (m^2 s^{-1}) the molecular diffusivity for heat in air, w = 0.15 (m) the leaf width, R=8.314 (J mol^{-1} K^{-1}) the universal gas constant and T_K is the leaf temperature in Kelvin.

Similarly g_{bHu} the boundary layer conductance for forced convection (mol m^{-2} s^{-1}):

$$g_{bHu} = 0.003\sqrt{\frac{U}{w}}\left(\frac{rP}{RT_K}\right) \quad \text{(A42)}$$

U being the wind speed (m s^{-1}) and g_r the radiative conductance (mol m^{-2} s^{-1}):

$$g_r = 4\varepsilon_l\sigma(T_a + 273.15)^4 k_d e^{-k_d SL} + e^{-k_d(L-L^+)} \quad \text{(A43)}$$

with σ the Stefan-Boltzmann constant, L the tree level leaf area index and L^+ the cumulative leaf area shading above a sub-canopy tree (for canopy trees L^+=0).

The boundary layer conductance to water vapour is estimated by: g_{bV}= 1.075 (g_{bHf}+g_{bHu})/0.5 (A44)

Ultimately the latent heat flux per unit leaf area (λE Wm^{-2}) is given according to the Penman-Monteith equation:

$$\lambda E = \frac{s\mathrm{R_n} + g_H c_P \rho_a D_C}{s + \gamma\, g_H / g_V} \quad \text{(A45)}$$

whereλ the latent heat of evaporation, R_n the net isothermal radiation (W m^{-2}),c_P the heat capacity of the air (J kg^{-1} K^{-1}), ρ_a the air density (kg m^{-3}), s the slope of the saturation vapour pressure to temperature curve (Pa K^{-1}), γ the psychometric constant (Pa K^{-1}) and g_H, g_V expressed in (m s^{-1}).

Table of Symbols

Tree Architecture and Functional Configuration		
Symbol	**Variable**	**Unit, Value**
d	Tree Diameter at breast height	cm
H	Tree Height	m
C_A	Tree Crown Area	m^2
C_{Amax}	Maximum Crown Area	m^2
C_D	Crown Depth	m
C_V	Crown Volume	m^3
L_D	Tree foliage density	$m^2\ m^{-3}$
L_A	Tree foliage area	m^2
L	Tree Leaf Area Index	$m^2\ m^{-2}$
M_a	Leaf dry mass per area	$g\ m^{-2}$
N_{Lm}	Leaf dry mass nitrogen content	$mg\ g^{-1}$
N_s	Stem dry mass nitrogen content	$mg\ g^{-1}$
N_R	Root dry mass nitrogen content	$mg\ g^{-1}$
P_{Lm}	Leaf dry mass phosphorus content	$mg\ g^{-1}$
D_W	Wood density of the stem	$g\ cm^{-3}$
α_S, β_S	Scaling coefficients for stem N content	(-)
α_R, β_R	Scaling coefficients for root N content	(-)
B_{ABG}	Tree above ground biomass	kg
B_L	Tree Total Leaf biomass	kg
B_S	Tree Stem biomass	kg
B_R	Tree Total root biomass	kg
B_{CR}	Tree Coarse root biomass	Kg
B_{FR}	Tree Fine root biomass	kg
Z_R	Tree Root Depth	mm

Radiation Balance Submodel		
Symbol	**Variable**	**Unit, Value**
Z*	Canopy height from the perfect plasticity model	m
k_b	Direct beam radiation extinction coefficient (black leaves)	0.50 (-)
k_b^*	Direct beam radiation extinction coefficient	0.46 (-)
k_d	Diffuse radiation extinction coefficient (black leaves)	0.78 (-)
k_d^*	Diffuse radiation extinction coefficient	0.719 (-)
ρ_b	Direct beam radiation reflection coefficient	(-)
ρ_d	Diffuse radiation reflection coefficient	0.036
ω	Scattering coefficient of the leaves	0.150
ε_l	Emissivity of the leaf	0.96
ε_a	Emissivity of the air	(-)
ε_s	Emissivity of the soil	0.94 (-)
Q_b	Incoming direct beam radiation	$W\ m^{-2}$
Q_d	Incoming diffuse radiation	$W\ m^{-2}$
S_{can}	Absorbed shortwave radiation from a canopy tree	$W\ m^{-2}$
S_{sub}	Absorbed shortwave radiation from a subcanopy tree	$W\ m^{-2}$
L_{sun}	Absorbed longwave radiation from a canopy tree	$W\ m^{-2}$
L_{shade}	Absorbed longwave radiation from a subcanopy tree	$W\ m^{-2}$

Photosynthesis & Respiration Submodels		
Symbol	**Variable**	**Unit, Value**
C_c	CO_2 concentration in the chloroplast	µmol mol^{-1}
C_a	Atmospheric CO_2 concentration	µmol mol^{-1}
T_L	Leaf temperature	^oC
I_O	PAR reaching the top of the tree canopy	µmol quanta $m^{-2}s^{-1}$
I_2	Absorbed irradiance by photosystem II	µmol quanta $m^{-2}s^{-1}$
ϑ	Curvature factor	0.7 (-)
D_c	Vapour pressure deficit between the canopy and the air	mol mol^{-1}
VPD	Vapour pressure deficit of the air	Pa
g_s , $g_{s,max}$	Stomatal and maximum stomatal conductance	mol m^{-2} s^{-1}
J, J_{max}	Electron transport rate and maximum electron transport rate	µmol m^{-2} s^{-1}
V_{cmax}, V_{Cmax}	Leaf and Canopy maximum carboxylation rates	µmol m^{-2} s^{-1}
a_{NV}	Empirical coefficient from the Domingues et al. 2010 model	-1.16 (µmol m^{-2} s^{-1})
v_{NV}	Empirical coefficient from the Domingues et al. 2010 model	0.70 (µmol mg^{-1} s^{-1})
a_{PV}	Empirical coefficient from the Domingues et al. 2010 model	-0.30 (µmol m^{-2} s^{-1})
v_{PV}	Empirical coefficient from the Domingues et al. 2010 model	0.85 (µmol mg^{-1} s^{-1})
a_{NJ}	Empirical coefficient from the Domingues et al. 2010 model	–1.22 (µmol m^{-2} s^{-1})
v_{NJ}	Empirical coefficient from the Domingues et al. 2010 model	0.92 (µmol mg^{-1} s^{-1})
a_{PJ}	Empirical coefficient from the Domingues et al. 2010 model	–0.11 (µmol m^{-2} s^{-1})
v_{PJ}	Empirical coefficient from the Domingues et al. 2010 model	0.66 (µmol mg^{-1} s^{-1})
k_V	Empirical coefficient from the Lloyd et al. 2009 model	(-)
k_N	Empirical coefficient from the Lloyd et al. 2009 model	(-)
Γ^*	CO_2 compensation point	µmol mol^{-1}
K_C	Michaelis-Menton carboxylation constant	µmol mol^{-1}
K_O	Michaelis-Menton oxygenation constant	mmol mol^{-1}
g_0, g_1	Empirical coefficients in Medlyn et al. 2011 conductance model	mol m^{-2} s^{-1}, (-)
g_H	Total leaf conductance to heat	mol m^{-2} s^{-1}
g_{bHf}	Boundary layer conductance for free convection	mol m^{-2} s^{-1}
g_{bHu}	Boundary layer conductance for forced convection	mol m^{-2} s^{-1}
g_r	Radiative conductance	mol m^{-2} s^{-1}
A_n	Rate of net photosynthetic carbon assimilation	µmol m^{-2} s^{-1}
A_v	Rubisco limited photosynthetic rate	µmol m^{-2} s^{-1}
A_j	Electron transfer limited photosynthetic rate	µmol m^{-2} s^{-1}
A_{day}	Daily total photosynthetic carbon assimilation	kgC d^{-1}
R_m	Total tree maintenance respiration	kgC d^{-1}
R_{mL}	Foliage maintenance respiration	µmol m^{-2} s^{-1}
R_{mS}	Stem maintenance respiration	µmol m^{-2} s^{-1}
R_{mCR}	Coarse root maintenance respiration	µmol m^{-2} s^{-1}
R_{mFR}	Fine root maintenance respiration	µmol m^{-2} s^{-1}
G,H	Empirical coefficients for the Mori respiration model	
a_{SS} , a_{RS}	Sapwood fraction of stem and root biomass	0.025
τ_S, σ_S	Empirical coefficients for the Reich stem respiration model	
τ_R , σ_R	Empirical coefficients for the Reich root respiration model	

Climate & Water Balance Submodels		
Symbol	**Variable**	**Unit, Value**
Pr	Atmospheric pressure	Pa
T_m	Mean daily air temperature	^oC
P	Total daily precipitation	mm
Q	Run Off	mm
E_{tot}	Total Stand Transpiration	mm
ϑ_i	Daily water content available to tree i	mm
ϑ_W	Water content at wilting point	mm
ϑ_{FC}	Water content at field capacity	mm
γ	Water stress term	(-)
Z_S	Soil Depth	mm

Supplement S2: Additional TFS simulations and figures

Figure S2.1: Observed (grey) against simulated (red) histograms of annual NPP allocated to stem growth at each one of the 7 intensive measurements plots. Plots are classified to a fertile and an infertile group based on the site score of the first PCA axis (Fyllas et al., 2009), with upper panel illustrating high fertility plots and lower panel illustrating low fertility plots.

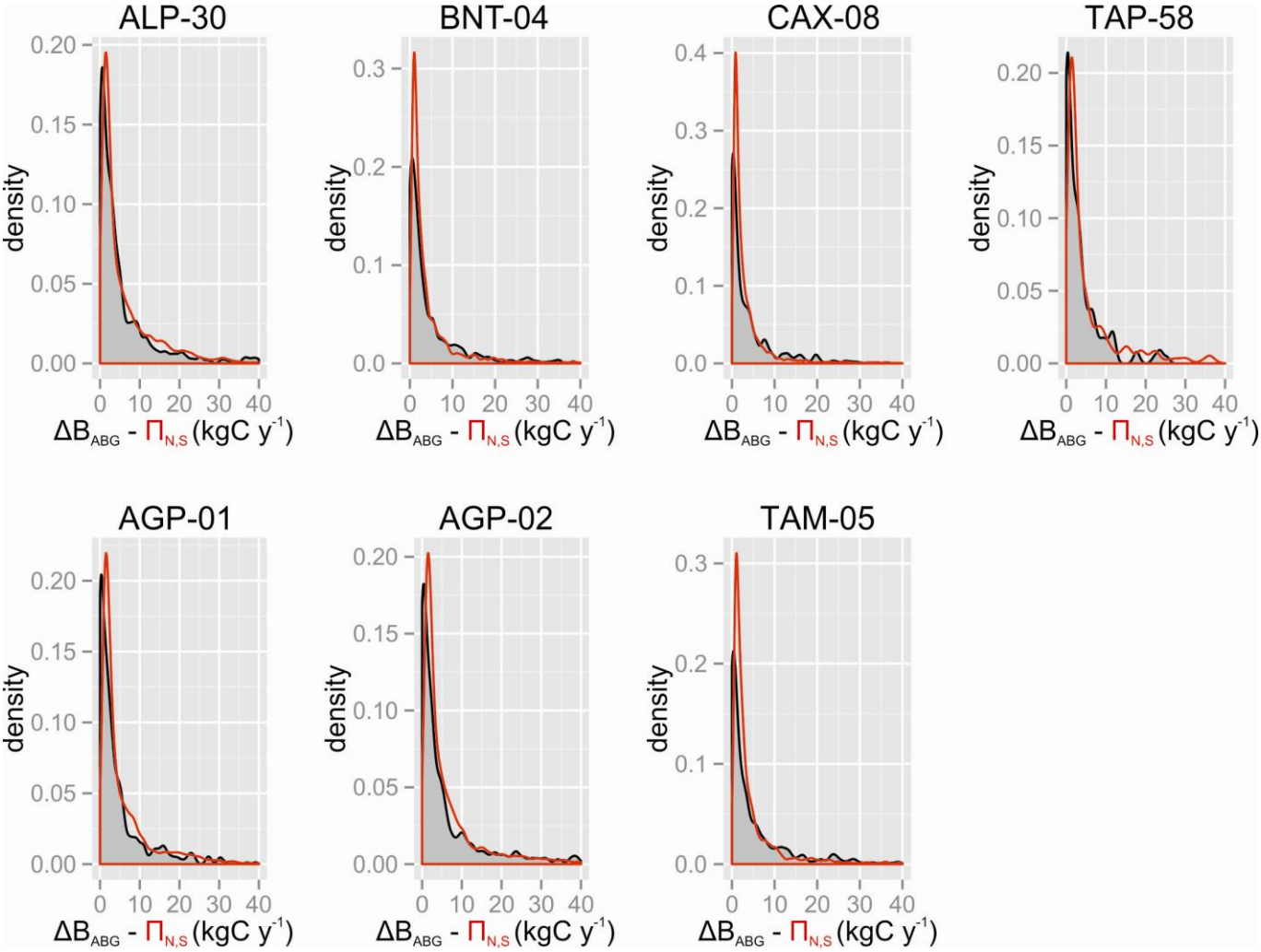
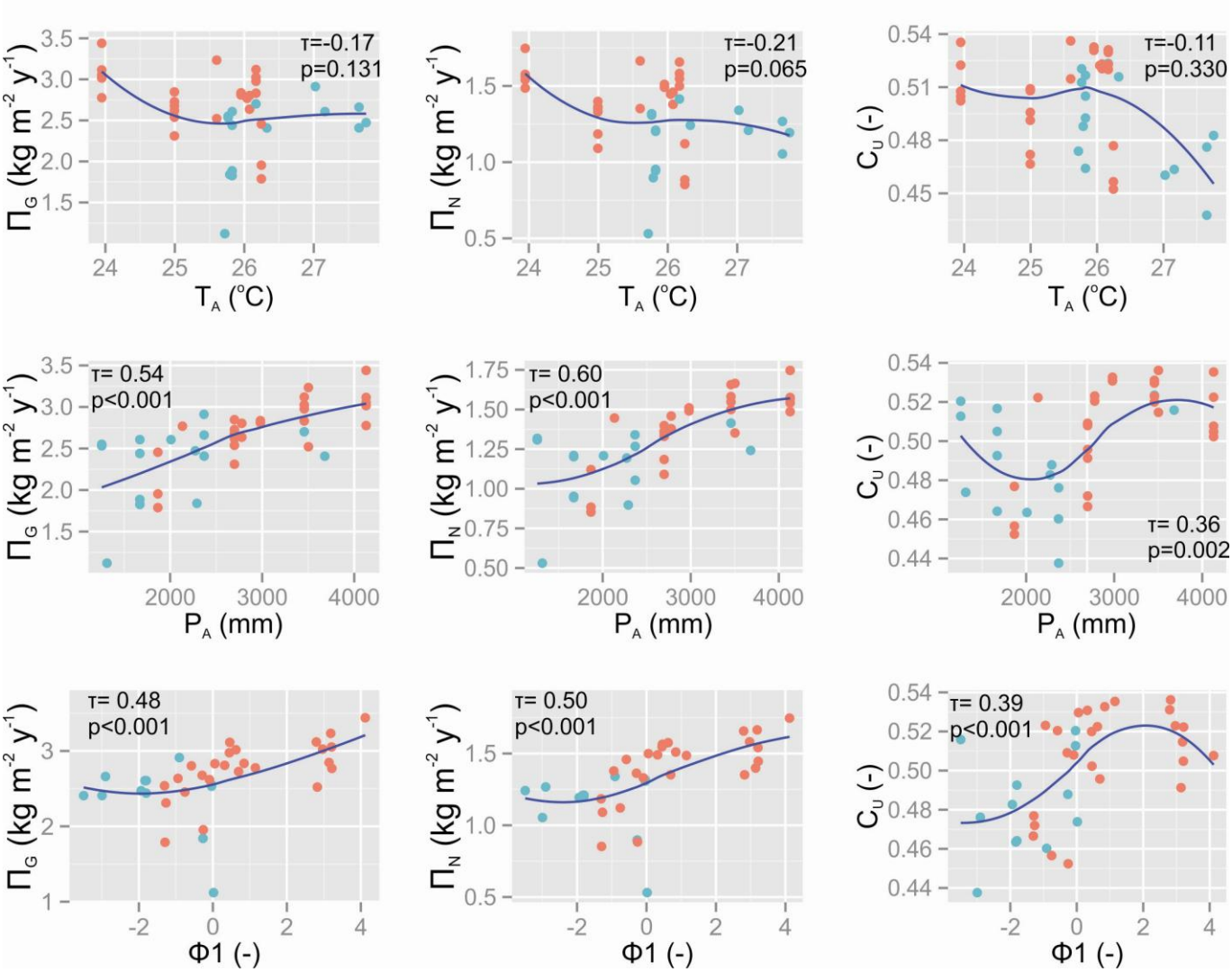


Figure S2.2: Simulated gross primary productivity (Π_G kgC m^{-2} y^{-1}), net primary productivity (Π_N kgC m^{-2} y^{-1}) and carbon use efficiency (C_U), along the annual temperature (T_A ^oC), annual precipitation (P_A mm) and fertility gradients (Φ_1) found across the 40 permanent measurement RAINFOR plots. Red dots indicate fertile plots while blue dots indicate infertile ones.



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